MAGNETISM

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MAGNETISM

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SIGMA

Sigma Introductions to Science 12

Sigma Books Limited
7 John Street, Bloomsbury,
London, W.C.1

First published 1949

PRINTED IN GREAT BRITAIN BY A. S. ATKINSON LTD., LONDON
AND BOUND BY THE LEIGHTON-STRAKER BOOKBINDING CO., LTD., LONDON

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the valuable information, advice, and criticism I have had from several of my friends and colleagues, and in particular I wish to thank my wife for criticizing the manuscript from the point of view of a non-physicist, thus helping to remove many obscurities which were not obvious to those more familiar with the subject.

I should like also to express my gratitude to Mr. E. L. Parry for producing such clear diagrams from my very rough sketches, to Mr. W. H. Andrews, of the Cavendish Laboratory, for taking or copying many of the photographs for the half-tone illustrations, to the following for lending original photographs : Professor L. W. Alvarez (Radiation Laboratory, University of California) for plate VII (*c*), Dr. J. Ashmead (Mond Laboratory, Cambridge) for plate V (*b*), Professor P. Bicquard (Paris) for plate III (*b*) and (*c*), Professor T. Bjerge (Copenhagen) for plate II (*b*), Dr. R. M. Bozorth (Bell Telephone Laboratories) for Plate I (*d*) and (*e*), Professor A. Cotton (Bellevue) for plate VII (*a*), Mr. C. G. B. Garrett (Mond Laboratory, Cambridge) for plate V (*c*), Mr. D. Hadfield (William Jessop & Sons) for plate VI (*b*) (*c*) (*d*) and (*e*), Dr. C. J. Milner (B.T.H. Research Laboratory) for plate VIII (*a*) (*b*) and (*c*), Dr. W. G. Radley (G.P.O. Research Station) for plate VIII (*d*), Professor S. Rosenblum (Bellevue) for plate VI (*a*), Mr. F. P. White (St. John's College, Cambridge) for plate II (*a*), and to Professor W. C. Elmore and the editors of the Physical Review for permission to reproduce plate I (*b*) and (*c*).

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LIST OF PLATES

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THE USE OF TECHNICAL TERMS AND MATHEMATICS

EVERY science introduces many special concepts of its own, and inevitably introduces also special names, or technical terms to describe these new concepts. This is not done for the sake of making the science respectable by clothing it in a jargon incomprehensible to the layman, but for the more sensible reason that it allows the exposition to be concise and avoids the tedious circumlocutions which would otherwise be necessary. In this book on magnetism many technical terms are introduced for just this reason and, once explained, they are used quite freely without any repetition of the definition. It is important to bear in mind the precise meaning of all such technical terms ; to help in this direction every new technical term is italicized at the place where it first appears or is first discussed, and at the end of the book all these definitions are collected together in a glossary (which also serves as an index) with references to the places at which they first appear.

Some readers may wonder why mathematical symbols and formulæ have been introduced in what is intended to be a book for the layman. One reason is similar to that for introducing technical terms : just as a technical term is a concise way of expressing a complicated idea, so the mathematical symbol is a kind of shorthand for a technical term. Once this shorthand is adopted (and it is not difficult to grasp, since the

explanation of every symbol is often repeated) it is possible to combine symbols into simple formulæ, and such formulæ often summarize important physical results more elegantly and compactly than any description in words can do.

Another reason is that the use of symbols and formulæ makes possible the estimation of how big the various things we shall talk about really are. A knowledge of the orders of magnitude of these quantities is a great help in understanding what they mean, and the best way of appreciating such orders of magnitude is to calculate them. Sometimes the appropriate calculation is difficult, and then we have to be content with saying "it turns out that," without any detailed explanation. Often, however (and especially if complicating details are ignored), the calculation involves no more than the simplest operations of algebra: multiplication, division, addition and subtraction. In such cases the simple mathematics adds conviction to a result which would otherwise have to be taken on trust, and it is also useful in giving some insight into the way physics can predict quantitative results.

The mathematics used in this book is rarely more complicated than simple algebra and arithmetic, but in the chapter dealing with the earth's magnetism, a little trigonometry is very helpful in explaining how this magnetism varies over the earth's surface and trigonometry is also sometimes introduced in footnotes to amplify the simplified treatment of the text. No attempt is made to work out any formulæ involving trigonometry, but some results involving sines, cosines and tangents of angles are quoted and used without proof. For those who have forgotten their trigonometry the appended diagram may be useful as a reminder, and a diagram is also added to illustrate the meaning of π, a symbol which will often come into the calculations.

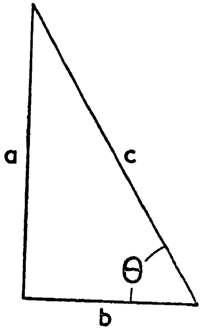


Fig. 1.—Illustrating simple trigonometry :
$\sin\theta = a/c$
$\cos\theta = b/c$
$\tan\theta = \sin\theta/\cos\theta = a/b$
The scale of drawing the triangle does not matter since only ratios are involved in the definitions.

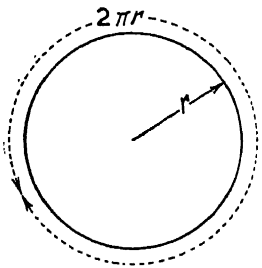


Fig. 2.—π is the ratio of the circumference to the diameter ($2r$) of the circle. Any circle will do since the ratio does not depend on the size. Numerically, π is about 3·14. Note, too, that the area of the circle is πr^2.

Chapter One

WHAT MAGNETISM IS ABOUT

EVERY child has at one time or another played with a magnet and been fascinated by its mysterious ways. It is almost uncanny to feel the repulsion between the like poles of two strong magnets, or to see a magnet lift a piece of iron many times its own weight. If these effects are fascinating, even in this age of radio and aeroplanes, when all sorts of mechanical wonders are accepted as commonplace, how much more fascinating must they not have appeared to the shepherd Magnes who first discovered, more than 2,500 years ago, that a rock of the naturally occurring magnet, *lodestone*, had a strong attraction for his iron crook?* It is not surprising that all sorts of magical qualities have been attributed to the lodestone through the ages. Some of these superstitions are still vaguely believed in to this day, and it may be as well before getting down to the question of what magnetism is about, to point out what it is not about.

Sir Thomas Browne, a 17th century philosopher, made an interesting collection of "vulgar errors" current in his time, and among them magnetic superstitions are well to the fore. A surprising variety of curative and other properties were attributed to the lodestone; for instance, "half a dram of lodestone given with honey and water proves a purgative medicine and evacuateth gross humours." Since the lodestone

* This is Pliny's version of the discovery of magnetism (and of the origin of the name), but Lucretius says that the name owes its origin to the country Magnesia in which the lodestone was first discovered.

attracted iron, it was believed that it could draw pain out of the body and was recommened as an amulet for headaches. Wounds made with a weapon which had been magnetized by a lodestone caused no pain (though other authorities held that such wounds failed to heal). The lodestone could cure gout, dropsy and hernias, and was even " a medicine of venereal attraction." Some held that lodestone was a poison, but against this " the King of Zeilan hath all his meat served up in dishes of loadstone and conceives thereby he preserveth the vigour of his youth." More recently the psychological phenomena of hypnotism and telepathy (if it exists) have been vaguely associated with magnetism following Mesmer, who built up a whole theory of this kind. The expression " a magnetic personality " has gained currency, and is sometimes thought to have more than a figurative meaning, as if some magnetic quality emanated from one person to another. Muddled thinking led also to the idea that magnets were not subject to the ordinary laws of nature. For instance, it was said that " if unto ten ounces of loadstone one of iron be added, it increaseth not unto eleven but weighs ten ounces still " and it was believed that lodestones attracted only by night.

The currency of such legends was due to the absence of a scientific attitude and to an uncritical belief in hypotheses based on false analogies without resort to the criterion of simple experiment. Browne was himself one of the early advocates of a more scientific approach and himself disproved by direct experiment some of the legends he quotes, though he, too, often preferred to discuss them on a purely metaphysical plane. The fact of the matter is that magnetism has no known direct effect on biological or psychological processes. Neither has it any magical effects, however disappointing it may be to reject such superstitions as one quoted by Browne that a wife's infidelity may be

discovered by putting a magnet under her pillow, which magically prevents her from staying in bed with her husband.

What then is magnetism about? Until about a century ago knowledge of magnetism was limited to the behaviour of permanent magnets—what we now call *magnetostatics*. It was known that a permanent magnet behaved as if it had two poles, and that like poles of two different magnets repelled each other while unlike poles attracted each other. If a piece of ordinary iron (or of any other "ferromagnetic" such as nickel or cobalt) was brought near to a permanent magnet, it became temporarily a magnet itself. This *induced magnetism* was however nearly completely lost again on removal from the permanent magnet. If more intimate contact was made by rubbing the iron against the permanent magnet, only part of the induced magnetism was lost on removal, and the iron remained itself a permanent magnet (usually only a weak one) indefinitely.

It was known too that a freely pivoted magnet (e.g. a compass needle) always set itself with its poles pointing north and south. This was for a long time thought to be an independent fact until William Gilbert, in the 17th century, following up some early experiments of Peter Peregrinus in the 13th century, showed that it was really a special case of the action of one magnet on another. The earth was in fact a large permanent magnet with its magnetic poles approximately at the geographical poles (the points in which the earth's axis of rotation meets its surface). The properties of the earth as a magnet were important for the first practical application of magnetism—the use of the compass for navigation. Although the use of the mariners' compass was known some 1,000 years ago—it seems to have come from China by way of Arab seamen trading with the west—this application

was little developed until the rapid development of mercantile trade provided a stimulus for further investigation.

Following on Gilbert's fundamental work, John Michell and Coulomb in the 18th century discovered the quantitative law of attraction and repulsion between poles—the famous "inverse square law." Finally Poisson, Gauss and other 19th-century scientists formulated all these results into an elegant mathematical theory which enabled the effects of any magnet to be precisely calculated. The science of magnetostatics was complete, though as yet there was no theory as to the real nature of magnetism.

A new era was opened up by Oersted's discovery in 1820 that an electric current produced magnetic effects. Ampère soon afterwards formulated this result very neatly by showing that any circuit carrying an electric current behaved just like an equivalent magnet, and Faraday made the further discovery that a moving magnet could generate electricity. The mathematical development of these intimate connections between electricity and magnetism was carried out by Clerk Maxwell, and led to far-reaching consequences, such as the discovery of wireless waves and an explanation of the nature of light.

At this stage it can be said that the classical theory, the theory of the electromagnetic field as it is usually called, was complete. It was clear that magnetism was in a sense a by-product of electricity—an interaction between electric currents or electric charges in motion; but much remained to be explained. What were the electric currents which caused induced and permanent magnetism? Why did different substances have such widely different magnetic properties? Some, such as the *ferromagnetics*, were capable of becoming permanent magnets or acquiring a strong induced magnetism, while others could not apparently be

magnetized at all. A great step forward was made by Faraday who showed that the last statement was not strictly true. He found that all substances could acquire a feeble induced magnetism of an amount characteristic of the particular substance and usually many thousands of times less than the amount characteristic of ferromagnetics, but only the ferromagnetics could retain any permanent magnetism.

Even before Faraday's discovery, Ampère had made a bold attempt to explain the magnetic properties of matter. Since electric circuits were equivalent to magnets, perhaps the magnetism of matter was due to electric currents circulating in the atoms of which the matter is made. This suggestion could not, however, be taken up seriously for nearly a century, since nothing was known in Ampère's time about the properties of atoms; only speculation was possible. Further development had to await the fundamental discoveries of recent times regarding the structure of matter. It was only with the growth of the atomic theory of matter, followed by the work of J. J. Thomson, Rutherford and Bohr on the structure of atoms themselves, that a real theory emerged. The turning point was in 1905 when Langevin produced a theory which explained a great deal of the data on magnetic properties of substances which had been amassed since Faraday's time, particularly by Pierre Curie. Since then there has been steady progress and although many obscure points of detail still remain, it can be said that in principle the magnetic properties of matter are now fairly well understood. Ampère's suggestion proved right in principle. Different substances have different kinds of atoms, and moreover these atoms may be linked in a variety of ways according as the substance is gas, liquid or solid, so it is not surprising that there is a corresponding variety of magnetic properties.

A rather surprising aspect of the modern atomic

interpretation is the very special position of ferromagnetism. It turns out that ferromagnetics can occur only in very special circumstances of atomic structure; that is why in fact only so few substances are ferromagnetic. Indeed, in a way, it is rather a fluke that ferromagnetics occur at all. Thus although these ferromagnetics were the only magnetic substances known until a century ago, and although they are of immense practical importance, they will not feature as prominently as might be expected in a logical development of the general theory of magnetism. In fact their properties can be understood only after the feeble magnetism of ordinary substances has been explained: an order which reverses the historical order of the basic discoveries.

Magnetism occupies an important place in science. On the one hand the study of the interactions between electricity and magnetism—the theory of the electromagnetic field—has led to a clear understanding of a whole range of phenomena in electricity and optics, which can now be explained in terms of very few basic principles. On the other hand the elucidation of the magnetic properties of matter in terms of atomic structure has been a valuable aid in the development of atomic theory. We shall see later that it has sometimes in fact been the magnetic properties which have taken the lead, and pointed the way to a better understanding of atomic structure.

This, however, is by no means the whole importance of magnetism in science. The modern scientist requires a host of technical devices for his experiments, and here magnetism plays an important part as a tool. These practical applications of magnetism are of immense service, not only to science, but even more so to modern technology, and a surprising number of devices which concern our everyday life are based on some aspect or other of magnetism. These range from

the dynamo, the electric motor, the telephone and other electrical equipment to such recent developments as the degaussing of ships to safeguard them against magnetic mines, radar and even the atomic bomb, all of which have played their part in winning the war.

We have seen that in the purely academic sphere, the importance of magnetism has been two-fold, the theory of the electromagnetic field (the "field" aspect) and the "properties of matter" aspect both playing their parts. This duplicity is reflected in the practical applications too, though usually in any particular application both aspects appear together. Almost every device involves the "field" aspect in its general principles; thus, for instance, the electric motor depends on the principle that a magnet exerts a force on an electric current. The "properties of matter" aspect is however equally involved in order that the utilization of the principle should be as efficient as possible; thus the electric motor will be efficient and powerful only if the most suitable magnetic materials have been chosen in its construction. Usually it is only ferromagnetic materials, whose properties are involved, but occasionally even the feebly magnetic substances are required, as for instance in the recently developed method of achieving super-low temperatures, which has opened up a whole new field of scientific investigation.

In this brief survey of the whole subject we have followed the historical order of the developments, and have given some indication of their general scientific and practical importance. For the more detailed treatment of the subsequent chapters it will, however, be more satisfactory to develop the subject in a logical rather than a historical order, starting from the electromagnetic field, then going on to the magnetic properties of matter, and finally to the scientific and practical applications. This introduction will have served its purpose if it has whetted the reader's curiosity; we hope he will find his curiosity satisfied in what follows.

Chapter Two

ELECTRICITY AND MAGNETISM: THE TWIN SCIENCES

1. *Magnetic poles and the inverse square law*

THE force which one magnet exerts on another provides a convenient starting point for a detailed study of magnetism, just as it did for the general survey of the last chapter. The first fact which comes out of simple experiments is that the force seems to emanate mostly from the two ends of the one magnet and is exerted mostly on the two ends of the other magnet; the ends are called the *poles* of the magnet. The two poles of a magnet are equally strong but have opposite effects: if one of them is brought up to a particular pole of the other magnet it produces an attractive force, while the other produces an equal repulsive force.

If the experiments are extended by introducing several more magnets it can be easily shown that like poles always repel each other, while unlike poles attract each other (the "likeness" of poles can be identified by their "likeness" of behaviour when brought up to a particular pole of one of the magnets). It is convenient to have a convention for labelling the two kinds of poles which occur, and for this purpose use is made of the fact that the earth is itself a magnet with its poles roughly at the geographical poles. If a magnet is freely suspended or pivoted it swings round till it points north and south, on account of the attraction of the earth's poles for the unlike poles of the magnet. The convention usually adopted is to call

the pole which points north, the north pole, and the pole which points south, the south pole, but it should be noticed that this is not entirely logical, since, of course, it implies that the geographical north pole is the south magnetic pole of the earth.

How large is the force between two poles? The experimental solution of this problem is complicated by the fact that a pole never exists in isolation, for there is always an opposite pole of equal strength at the other end of the magnet. If, for instance, we measure the force between two magnets, we must remember that it is made up of four forces between the pairs of poles. Fortunately the force between two poles falls off rapidly as they get further apart, so the complication can be reduced by experimenting with long magnets in which the poles are far apart. If then, two particular poles are brought relatively close together, most of the force between the magnets will come from the force between these particular poles since the other two are too far off to have much effect. Experiments of this kind were first made by John Michell in 1750, and he discovered that the law of force is a very simple one: as the poles are approached, the force, whether repulsive or attractive, increases inversely as the square of the distance between them. If, for instance, in bringing up one pole of a magnetized knitting needle to within 1 cm. of the like pole of another magnetized knitting needle, we found a repulsive force of 9 dynes*, then the force for a 3 cm. separation would be 1 dyne. This *inverse square law* is often called *Coulomb's law*, since Coulomb discovered it independently in 1785, unaware that he had been anticipated by Michell.

The force between the two poles depends not only

* The *dyne* is the unit or force used in the metric system (the cm., gm., sec. or C.G.S. system, as it is technically called) and it is roughly equal to the force of gravity acting on 1 milligram.

on their distance apart, but is also proportional to the strengths of the two poles. How is the pole strength of a magnet measured? Evidently, a logical unit of pole strength is one which exerts unit force (1 dyne in the C.G.S. system) on an equal pole, unit distance (1 cm.) away. If a pole exerts twice as much force in a particular position on some other pole, as a unit pole would do in the same conditions, we say its pole strength is 2. The pole strength of a powerful bar magnet of say 1 cm. diameter might be 300 unit poles, while the knitting needle of our previous example, being much thinner, might have a pole strength of only 3 unit poles (this was the figure assumed in the example). The inverse square law can be stated more completely as an equality: the force between two poles is equal to the product of the two pole strengths divided by the square of their distance apart. The definition of a unit pole is important not only in providing the basis of all the magnetic units of measurement, but as we shall see later is involved in many familiar electrical units such as the *ampere*, *volt* and so on.

2. *Magnetic field*

When the physicist has to deal with a new phenomenon, he often has recourse to the idea of a *field*. For instance, he speaks of a gravitational field, an electric field or a magnetic field and he finds this concept very useful in clarifying his ideas and formulating a quantitative theory. Just as a field of grass is a region where grass grows and a field of battle is a place where fighting goes on, so the physicist's field describes the existence of some physical effect in the region concerned. More precisely it is a measure of how strongly the effect occurs at any particular place. When we say that there is a magnetic field in the region round a magnet, we mean simply that the magnet has an action on a small probe magnet (such as a compass needle)

placed anywhere in the region, and the size of the field measures the strength of this action.

The simplest method of characterizing the strength of magnetic " action " is in terms of the force on a single pole, for the action on a magnet can then be built up from the forces on the separate poles. We therefore define the *magnetic field* at any place as the force that would be exerted on a single unit north pole placed there and it should be noticed that this definition involves not only a magnitude but also a direction—the direction in which the force acts. The unit of field-strength is called a *gauss* in honour of the scientist, C. F. Gauss, who contributed a great deal to the subject; it is the field strength 1 cm. away from a unit pole. To give some idea of orders of magnitude we may mention that the magnetic field of the earth in London is about 0·6 gauss, while the field close to the end of a strong permanent magnet* may be as high as 5,000 gauss, and with electromagnets, fields as high as 300,000 gauss have been produced.

Once the field at any place is known, both as regards strength and direction, the mechanical effect on a magnet placed there can easily be deduced by summing the effects on its separate poles. It is no longer necessary to know how the field is produced, and we can speak directly of the action of the field on the magnet instead of having to refer back to the magnet or system of magnets which produce the field. Suppose we hold a small bar magnet in a magnetic field in such a way that the field direction does not lie along the magnet (fig. 3*a*); the two poles then have equal but opposite forces acting on them which are not in line. In the language of mechanics, a *couple* acts on the

* At first sight it might seem that the field could be made infinite by going close enough to one pole, but this is not so because actually the pole strength is not concentrated in a point but is spread over an area at the end of the magnet. It can be shown that the field very close to such a spread out pole is $4\pi \times$ pole strength per unit area.

magnet and tends to twist it. If the magnet is released so that it can turn freely it will twist round until it is in line with the field (fig. 3*b*), when the twisting couple just disappears. In other words, a magnet which is freely suspended or pivoted comes to rest when it points in the field direction. In explaining why a freely suspended or pivoted magnet such as a compass needle points north and south, we could have said simply that the earth's magnetic field has the north-south direction.

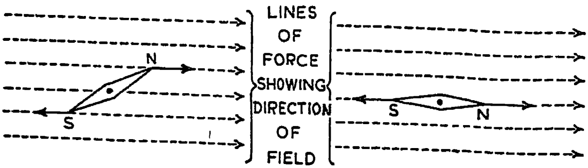


Fig. 3.

(*a*) When a magnet is at an angle to a magnetic field, equal and opposite forces act on its poles and produce a twisting couple.

(*b*) The magnet has now turned till the forces come into line, when it points along the field; it now has zero couple acting on it.

This property of a compass needle to point in the field direction provides a neat way of representing the magnetic field in a pictorial manner. If we move the compass needle about, always following the direction in which it points, it will trace out a curve, and with different starting points we can trace out as many curves as we please. These curves, whose directions are always those of the field at each point they pass, are called *lines of force*, and provide a kind of map of the magnetic field. A diagram of the lines of force round a bar magnet is shown in fig. 4. A rough picture of the same diagram can be obtained even

more simply by sprinkling iron filings round the magnet (see plate I *a*). Each filing becomes magnetized and acts like a little compass needle; if the table is tapped so that friction is momentarily eliminated, the filings are able to turn into the field direction and build up chains with each other which follow the lines of force.

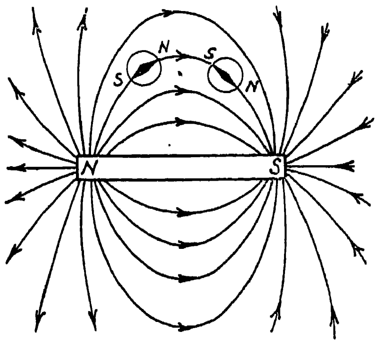


Fig. 4.—The lines of force of a bar magnet; a compass needle sets itself along the line of force passing through it.

If we examine fig. 4, we notice that near the poles the lines of force crowd together, while far away from the poles the lines are more spread out. This suggests that our "map" can be made to yield more than information about field direction, and indeed it turns out that the crowding or the "density" of the lines of force gives a measure of the field strength. This is best illustrated by considering a rather simpler case, the lines of force due to a single north pole. If our "probe" pole is placed anywhere in the neighbourhood of the first pole it is repelled along the line joining them, so the field direction must be everywhere radial and the lines of force must be straight lines radiating out from

the first pole like the spokes of a wheel (fig. 5). Actually the lines of force radiate out not merely in the plane of the diagram but in all directions and a pin cushion would be a more appropriate description. Imagine a

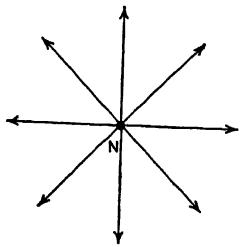


Fig. 5.—The lines of force of a single N pole.

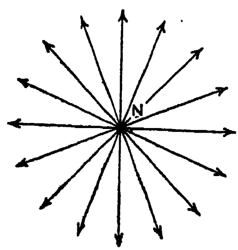


Fig. 6.—The same as fig. 5 but with twice as many lines drawn; the magnetic field is not changed by increasing the number of lines drawn.

sphere drawn round the pole as centre, then it is easy to see that the number of lines crossing unit area of the sphere (the "crowding" of the lines) decreases as the square of the radius of the sphere, or in other words it is proportional to the field strength. This is because all the lines start from the pole, and none are lost on the way, so the number crossing the sphere

is the same whatever the radius, while the area of the sphere increases as the square of its radius. We saw just now that we can draw as many lines of force as we please, and it may seem confusing that in spite of this we speak of density of lines of forces. Actually what we really mean is relative density, for even if, as in fig. 6, we draw twice as many lines as in fig. 5, the relation between the densities at different places are not affected, so our argument does not depend on how many lines we choose to draw.

What happens if we put one magnetic field on top of another? If for instance there are two magnets instead of one, we can think of the field at any place as made up of out of the field of each magnet acting separately. Thus if we put a "probe" unit pole at this point there will be two forces acting on it. The two forces can be combined into a single *resultant* by the rules of mechanics ; the method of combination is the *parallelogram of forces* illustrated in fig. 7 and the resultant force then gives the combined field of the two magnets. In a precisely similar way the

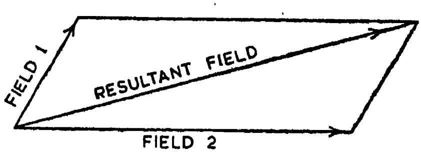


Fig. 7.—The parallelogram of forces, showing how to combine fields in different directions. Each arrow represents the magnitude and direction of the appropriate field.

lines of force of fig. 4 could have been constructed by combining the lines of force of two opposite poles, as shown in fig. 8. This method of combining forces or fields is important enough to have a special name, and it is called *vectorial addition*. It is carried out

not by just adding the field strengths as in arithmetic, but by taking their directions into account also, as explained in fig. 7.

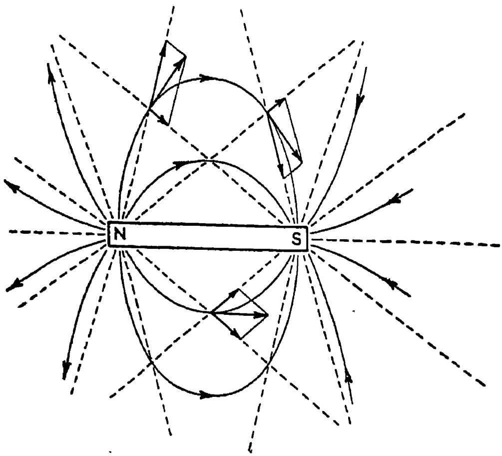


Fig. 8.—The lines of force of a bar magnet (the full lines, as in fig. 4) can be constructed by combining the lines of force of the separate poles (the broken straight lines, as in fig. 5). The combination is done with the parallelogram of forces (fig. 7).

One other concept must be mentioned before leaving this part of the subject. This is the concept of a *uniform field*. A uniform field is one which has the same strength and direction at all places in the region. It is somewhat of an idealization, since in practice fields are never exactly uniform everywhere, but often it is possible to have a field that is to all intents and purposes uniform over a large region. The lines of force of such a field are very simple, just a series of

parallel straight lines, as shown in fig. 9, and an example of a uniform field in practice is the earth's field. Since the earth's field runs from south to north,*

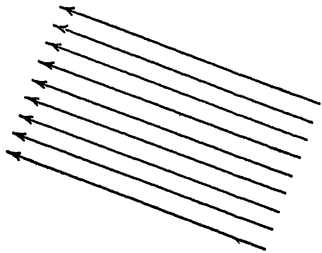


Fig. 9.—The lines of force of a uniform field are parallel, straight, equally spaced lines.

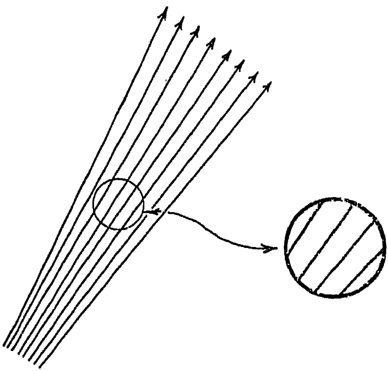


Fig. 10.—Over a small region (the circle, shown enlarged at the side) the field is very nearly uniform, even though the field is appreciably non-uniform over a larger region.

* Strictly speaking, it is only the horizontal component of the earth's field which runs from south to north. We shall see later (*p*. 136) that the earth's field has a vertical component too.

the lines of force will be as parallel as the lines of longitude are. Provided we do not consider too large a region, the earth's field is very nearly uniform; if, however, we consider a very large region, for instance, the whole earth, then the lines are no longer parallel, and the field is no longer uniform. For that matter, any field can be considered as uniform if we limit ourselves to a small enough region, since inside such a small region the lines of force are always nearly parallel (see fig. 10). That is why we spoke of a "small" probe magnet, for we meant a magnet so small that the field could be considered as uniform all over it, and in explaining the use of a compass needle for plotting lines of force we assumed that the field was the same at both poles of the compass needle.

3. *Dipoles and Shells*

If we multiply the pole strength of a magnet by the distance between the poles (i.e. by the length of the magnet) we get a quantity called the *moment* of the magnet. At a distance from the magnet, large compared with its length, it turns out that the magnetic field depends only on this moment and the distance away. That is to say, the same field would be produced if the magnet length were halved and the pole strength doubled. If the magnet length is reduced indefinitely and the pole strength increased in proportion to keep the moment constant, so that the field is still the same, we have what is called a *dipole*. In other words the dipole is the limiting case of a very short magnet of finite moment, and for practical purposes we can think of it as just a short magnet, provided we keep the length much smaller than any other distances involved. The lines of force of a dipole are shown in fig. 11, and as we should expect, the diagram has some similarity to that for the magnet of fig. 4.

Instead of thinking of a magnet as made up of two poles separated by a distance, we can equally well think of it as built up of a large number of dipoles.

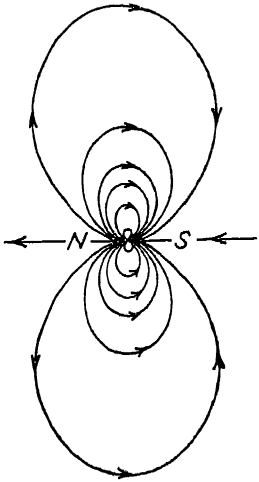


Fig. 11.—The lines of force of a magnetic dipole.

For instance, fig. 12 shows how a bar magnet can be considered as built up of a large number of smaller magnets packed end to end in rows with opposite poles touching each other. The effects of all the north poles in the interior of the large magnet are exactly

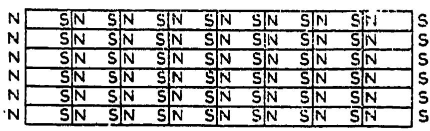


Fig. 12.—A bar magnet may be thought of as built up of many smaller magnets.

cancelled by the south poles which adjoin them and the net effect is due only to the poles at the two ends. If we think of every magnet as built up of dipoles in this way, it becomes obvious why, when a magnet is cut up into pieces, each separate piece remains a magnet with opposite poles. The total moment of the whole magnet divided by the volume of the magnet can be thought of as the dipole moment per unit volume—the sum of all the dipole moments contained in a unit volume of the large magnet. This dipole moment per unit volume will subsequently be very important, and it is called the *intensity of magnetization* of the magnet or sometimes more briefly the *magnetization*. It may at first sight seem unnecessarily complicated to replace the two poles of a magnet by a great number of dipoles, but actually the poles turn out to be a convenient fiction rather than a reality, a sort of scientific white lie in fact. The dipole picture is nearer to reality, and we shall see later that each atom of the magnet does in fact behave like a dipole. Even the dipoles are a bit of a white lie, for we shall see soon that an electric current circuit behaves like a dipole, and it is the circulating currents in the atoms that make a magnet behave like a dipole. Fortunately there is no harm in white lies, so long as we are careful not to believe them too literally.

Another arrangement of dipoles is one called a *magnetic shell*, which is important in understanding the magnetic effects of electricity. Instead of laying the dipoles end to end as in a bar magnet, imagine them packed together side by side with like poles together. We then get a thin sheet of dipoles as shown in fig. 13 (the sheet need not be plane), and this sheet is called a magnetic shell. The poles of the shell are spread all over its two faces, one face containing only north poles, and the other only south poles. The field of such a shell can be calculated ; it depends

only on the shape of the rim of the shell, and is proportional to the dipole moment per unit area of the

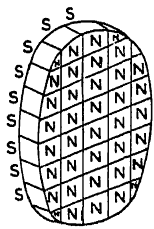


Fig. 13.—A magnetic shell may be pictured as made up of many short magnets side by side.

shell, or the *strength* of the shell as it is called. The field is the same for any shell of the same strength which has the same rim (as for instance the two shells of fig. 14). This idea may be a little difficult to grasp

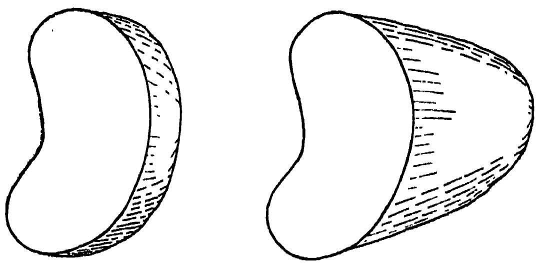


Fig. 14.—The magnetic field of a shell of given strength depends only on the shape of its rim ; the two shells illustrated would have the same fields.

at first, but a visual help is to think of the shell as a saucer with many little magnets studded through it in holes drilled through the saucer. The field of the

saucer will then be the same as that of any other surface, such as a pudding bowl or a flat plate, which has the same rim and the same number of magnets studded through it per unit area. The lines of force of a magnetic shell are shown in fig. 15. A property of magnetic shells that we shall need later is that if a unit north pole is taken along a line of force starting from one face (the south pole face) and finishing at the other, the work that has to be done is 4π times the shell strength.

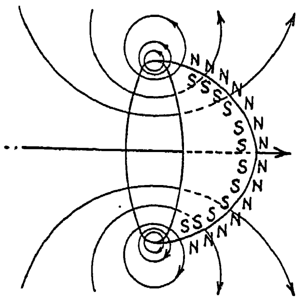


Fig. 15.—The lines of force of a magnetic shell.

4. *The magnetic effects of electricity*

The science of electricity can boast an ancestry as ancient as magnetism, but although the Greeks were familiar with the static electricity produced by friction, little progress was made in this science until comparatively recent times. There are two kinds of electric charges, positive and negative*, which in many ways behave very similarly to magnetic poles. Coulomb showed that electric charges exert a force on each other which, just as in the case of magnetic poles,

* It is sometimes more correct to describe positive electricity as due to a deficit of negative electricity, but this distinction is not relevant to the present account.

follows an inverse square law, and the concept of electric field as the force on a unit charge was also developed. An essential difference, however, is that positive or negative electric charges, unlike magnetic poles, can be separated and, moreover, may flow along metallic wires in the form of an electric current. With the discovery by Volta in 1800 of the electric pile, a forerunner of the modern electric battery, a convenient source of continuous electric current became available (previously only momentary currents could be produced when static electricity was " discharged ") and all sorts of new experiments became possible.

Oersted in Denmark had the idea that there might be some effect of electricity on magnets, but however inconceivable it is to-day that anyone looking for the effect could have missed it, it took Oersted twelve years of investigation to find the first effect in 1820. He has been described as " a man of genius, but a very unhappy experimenter " and it was largely by accident that he made the discovery at all. What he found was that a magnetic compass needle was deflected in the neighbourhood of a wire carrying an electric current—the wire behaved in fact like a magnet.

The quantitative development of this discovery was left to others, mostly the Frenchmen Biot and Savart and Ampère. By 1825, Ampère was able to give a comprehensive account of the whole phenomenon in a memoir which Maxwell has described as " perfect in form and unassailable in accuracy." Basically he showed that the current flowing in a circuit is equivalent in its magnetic effects to a magnetic shell which has the circuit as its rim and which has a strength proportional to the current. This simple formulation contains all the experimental results and permits the prediction of the magnetic field of any circuit we please. For instance, fig. 16 shows the lines of force that would result if an electric current flowed round a circular wire;

they are the same as those of the shell in fig. 15. The direction of the lines of force (indicated by arrows) is related to the sense in which the current flows by the *corkscrew rule* : the lines progress in the same way as does the point of a corkscrew which is being twisted in the sense of the current flow.

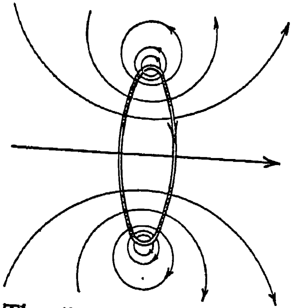


Fig. 16.—The lines of force of an electric current in a circular wire : the lines are the same as those of the shell in fig. 15.

We have seen that if a unit pole is taken along a line of force from one face of a magnetic shell back to the other the work done is 4π times the shell strength, and so an equivalent form of *Ampère's law* is that the work done in taking a unit pole round a closed path which interlaces the current circuit is $4\pi \times$ current*. Although the full content of Ampère's law cannot be appreciated without mathematical analysis, we can calculate the field in some simple cases by using this alternative formulation.

If, for instance, the electric current flows in a long straight wire, the lines of force in any plane perpen-

* We have assumed here that the current is measured in such units that the proportionality in Ampère's law is an equality, in other words that the strength of the equivalent shell is *equal* to the current. Some further explanation of this system of units will be given later (p. 43).

dicular to the wire are as shown in fig. 17. They are circles having the wire as centre, as we might guess by the symmetry of the arrangement, and we can calculate the field along any particular line of force by taking a

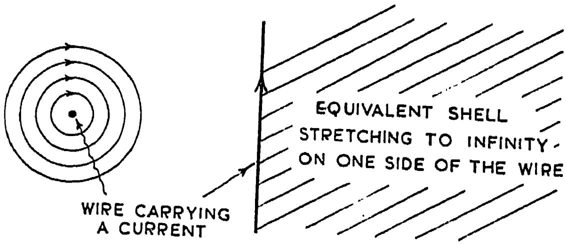


Fig. 17.—The lines of force round a straight wire carrying a current (flowing *into* the paper) are circles. The equivalent shell is shown on the right.

unit pole round it. By symmetry the field will have the same size all the way round and so the work done (which is force $\times$ distance) is field $\times$ circumference of circle. This, as we have seen, is just $4\pi \times$ current, so we deduce that the field is $2 \times$ current $\div$ radius (since the circumference is $2\pi \times$ radius); in symbols, if H is the field, i the current, and r the radius, $H=2i/r$. The equivalent magnetic shell in this case is a sheet having the wire as one edge and stretching out to infinity in all directions on one side, to take in the remote part of the circuit by which the current reaches the long wire.

Another important case is if the current flows in a coil of wire. We have already shown in fig. 16 the lines of force due to a single turn of wire; the field of the whole coil can be built up as the sum of the fields of its separate turns. If the coil is long compared

with its diameter (fig. 18) it is usually called a *solenoid.* Outside the solenoid the lines of force are very similar to those of a bar magnet ; inside, the lines become straight and evenly spaced. We see in fact that inside the solenoid the field is " uniform " in the sense explained on p. 20. If again we move a unit pole along a line force following it through the solenoid and right round outside till it comes back to the start,

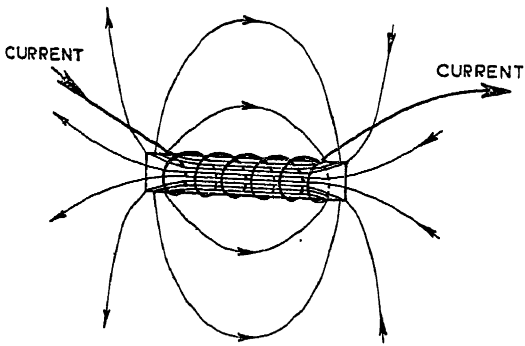


Fig. 18.—The lines of force of a solenoid resemble those of a bar magnet (fig. 4). The heavy lines show the wire coil carrying a current ; in practice the turns would be spaced much more closely.

most of the work will be done inside the solenoid, for, the field outside is quite small as can be seen from the spreading of the lines of force. Approximately, then, the work done will be field × length of solenoid and this must equal 4π × current × number of turns, since each one of the turns can be thought of as a separate circuit which is interlaced by the lines of force. Thus, the strength of the uniform field H, is given by 4π × number of turns per unit length × current ; in symbols, $H = 4\pi Ni/l$ where N is the number of turns, l the

solenoid length, and i the current. Actually this is a very good approximation if the length is several times the diameter. For a given density of winding (turns per unit length) the field does not depend on the length or diameter of the coil. The solenoid provides the simplest means of producing a fairly large uniform magnetic field over a large volume without the use of permanent magnets, and it is in fact the simplest case of an electromagnet. We shall see later that much greater fields can be produced with special arrangements in which the solenoid is wound on an iron core.

Another case is if the single turn of fig. 16 becomes small in area; this is important later in developing the atomic theory of magnetism. If the area of the circuit is small, the equivalent magnetic shell becomes small too and may be treated as if it were just a single dipole. Thus the field of such a small electric circuit is the same as that shown in fig. 11. The moment of the equivalent dipole is just current $\times$ circuit area, since the shell strength is equal to the current and shell strength is defined as dipole moment per unit area.

All the above results were deduced from Ampère's picture of an equivalent magnetic shell, but they can be derived also from another formulation due to Biot and Savart, which, although entirely equivalent to Ampère's formulation (one can be derived from the other), is for some purposes easier to deal with. Biot and Savart supposed the circuit to be broken up into small pieces—*current elements* as they are often called—and showed that each such element can be thought as producing a field given by current $\times$ length of element $\times$ sin $\theta \div$ square of distance (see fig. 19). This field, however, does not have the direction of the line joining the element to the point at which the field is being measured, as it would if we were concerned with the field of a pole, but is in a direction perpendicular to this line and perpendicular also to the element

(fig. 19). The total field due to the whole circuit at P in fig. 19 is the sum of all the fields contributed by the elements making up the circuit, added vectorially as explained in fig. 7.

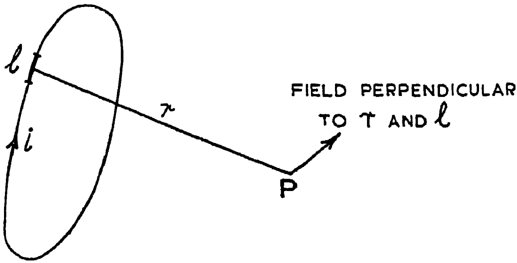


Fig. 19.—Illustrating how the magnetic field of a current can be thought of as the sum total of the fields due to each element of the circuit separately. The arrow shows the direction of the field produced by the particular element marked l : if r is at an angle θ to l, the magnitude of this field is $il\sin\theta/r^2$.

An easy example of how to apply this Biot-Savart method is the calculation of the field at the centre of a circular turn of wire carrying a current. In this case each element of the wire contributes a field at the centre equal to current × length of element ÷ square of radius, and all the contributions have the same direction perpendicular to the plane of the circular turn. Since all the directions are the same the vectorial addition becomes just ordinary addition, and the total field at the centre becomes current × total length of the turn ÷ square of radius, or since the total length is the circumference which is equal to 2π × radius, the field is 2π × current ÷ radius ; in symbols, $H = 2\pi i/r$. The previous examples and many others can be worked out in a similar way, but the calculation

is usually more complicated owing to the necessity of vectorial addition of the contributions from the various circuit elements.

The Biot-Savart formulation paves the way for understanding another important aspect of the interaction between electric currents and magnetic fields: the fact that a magnetic field exerts a mechanical force on an electric current. If we place a magnetic pole near an electric current circuit, the magnetic field of the current exerts a mechanical force on the pole, and so by Newton's law of mechanics that action and reaction are equal and opposite, this must mean that the pole equally exerts an opposite force on the circuit. The force acting on the pole due to an element of the circuit (l in fig. 19) is pole strength × current × element length ÷ square of distance (assuming for simplicity that $\theta=90°$), and so this must be also the force acting on the element. Now pole strength ÷ square of distance is just the value of the field due to the pole at the position of the element, so we see that the mechanical force acting on the element due to the pole is field of pole × current × element length. The direction of this force is perpendicular both to the line joining the pole to the element and to the element direction. If there is a number of different poles present (combined to make some arrangement of magnets) their forces on the element must be added vectorially. The result depends on the direction of the total field produced by the arrangement of magnets: if this total field is perpendicular to the element, the mechanical force is given by total field × current × element length, and is perpendicular to the field and to the element, but if the total field is in the direction of the element, the mechanical force is zero*. Having obtained the force on an element,

* In general the resultant force is total field × current × element length × sine of angle between field and element directions.

the total force on the whole circuit is given by the vectorial sum of the forces on all its elements. It should be noticed that in calculating the force on an element, we need not take account of the magnetic fields of the other elements of the same circuit, for the forces due to these fields will always cancel out when the total force on the whole circuit is added up. Just as you cannot lift yourself up by your own hair, so the current cannot exert any net force on itself, though it can of course produce internal stresses, just like the stresses produced in your body if you do try to lift yourself by your hair.

Another way of looking at this mechanical force is to think of the current circuit as equivalent to a magnet (Ampère's equivalent shell) and then the mechanical force exerted on it by other magnets becomes just the ordinary force between magnets. A simple example illustrates how both points of view lead to the same result. Consider a small rectangular current circuit placed in a uniform magnetic field parallel to its plane (fig. 20). By Ampère's law the circuit is equivalent to a dipole of moment given by current × area (as we saw on p. 31), and it will behave in the same way

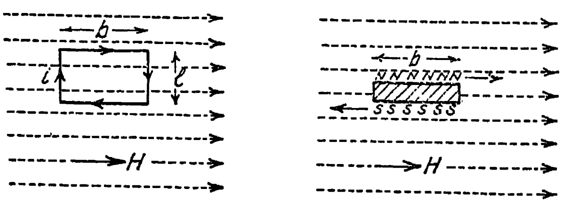


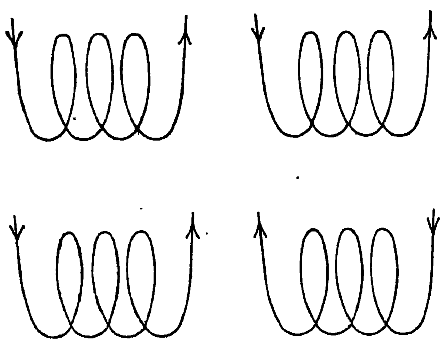
Fig. 20.—A rectangular coil of wire carrying a current tends to twist in a uniform magnetic field. The couple is given by $iblH$. The right-hand diagram is the view looking on the coil from above; the shaded area is shown of exaggerated thickness and represents the equivalent magnet.

as a short magnet of this moment placed perpendicular to the plane of the circuit. Extending the argument of p. 15, it is easily seen that the uniform field produces no net force on this equivalent magnet but only a couple given by moment × field, or current × area × field, tending to twist the coil. On the Biot-Savart formulation, we can think of the circuit as made up of four elements, namely its four sides. There are no forces on the two horizontal sides, since the current in them flows parallel to the field, while the forces on the two vertical sides are opposite (because the current flows up in one and down in the other) and each equal to current × length × field. These two opposing forces produce a twisting couple given by force × breadth, since the forces are separated by the breadth of the coil, so we find a couple given by current × area × field just as we did starting from Ampère's law.

The simple example of a rectangular coil illustrates the principle of a *galvanometer* or *ammeter* used to measure electric currents for, by measuring the twisting couple on the coil, we have a measure of the current flowing in it. If the coil is between pivots, but restrained by a spiral spring it will twist until the couple is balanced by the restoring couple due to the elasticity of the spring. The twist can be measured by attaching a long pointer to the coil and reading off the position of the end of the pointer. In practice the uniform field is obtained by putting the coil between the poles of a horse-shoe permanent magnet, and the sensitivity of the instrument can be increased by using a coil of many turns wound on an iron core.

Another important application based on the same general principle is the electric motor. In this case the rectangle (in practice a coil of many turns wound on an iron core to enhance the effect) is mounted so that it can turn freely. The couple then twists it until it

has turned through a right angle: at this stage the couple becomes zero since the opposing forces on the two vertical sides just come into line with each other. In order to keep the rotation going, some additional device must be used. For instance, if the direction of the current is reversed (by a device called a commutator) just as it gets to the "dead" position, the coil will turn a little further by inertia and then a couple again acts on it in the right direction to maintain the rotation. If the current is reversed each time the coil gets into the position perpendicular to the field, the rotation continues indefinitely, and we have a motor driven by electricity.



a

b

Fig. 21.—The coils in (*a*) will attract each other (currents flow in the same sense), those in (*b*) will repel each other (currents flow in opposite senses).

The action of a magnetic field on an electric current is not limited to fields produced by magnets. The force is still produced even if the field is due to other electric circuits (which, as we have seen, are equivalent to magnets). For instance, if two coils are placed side by side (fig. 21) they exert a force on one another :

an attraction if the current flows in a similar sense in both coils, and a repulsion if the sense is opposite. This effect, too, can be used to measure electric currents as in Kelvin's current balance, where the same current is made to flow through both coils, and the force is measured by an ordinary balance, but we mention it here for another reason. It suggests that the forces between magnets, the mysterious forces with which we started our account in Chaper 1, are really forces between current circuits in the atoms of the magnets.

As we shall see in more detail in Chapter 4, the modern view is that there is perhaps no such thing as magnetism in itself; it is in a sense a by-product of the electric currents in the atoms of matter. Instead of speaking of an electric circuit as being equivalent to a magnet, we should really say that a magnet is equivalent to a combination of electric circuits, and its properties are just the properties of these electric circuits. Notice, however, that we have not really solved the mystery of why magnets attract and repel each other, we have merely reduced it to the same mystery as that of why electric circuits exert forces on each other. This is typical of the way science progresses: scientific theory advances by explaining one effect in terms of another. Each new advance reduces the number of phenomena which have to be regarded as basic experimental facts, but the residue of independent basic facts still remains unexplained. Science will be complete when only a single basic principle is required to explain all phenomena in nature, but there is a long way to go before this goal is reached.

5. *The electrical effects of magnetism*

Ever since Oersted's discovery it was a tempting idea that if electricity could produce magnetism, then perhaps also magnetism could be used to generate electricity. The right conditions for this reverse

process, *electromagnetic induction* as it is called, were discovered eleven years later by Michael Faraday, the experimental genius who started his career as a laboratory assistant and became one of the greatest scientists of the nineteenth century. He found that if a magnet is moved near a wire circuit, or if a wire circuit is moved near a fixed magnet, an electric current appears in the circuit; the current is only momentary and stops when the motion stops. A series of clear-cut experiments in the course of only a few days enabled Faraday to formulate the basic features of the whole phenomenon.

Faraday's law was that the *electromotive force* (*E.M.F.* for short) which drives the induced current round the circuit is proportional to the rate of change of *magnetic flux* through the circuit with time. By magnetic flux is meant simply the magnetic field perpendicular to the plane of the circuit multiplied by the area of the circuit, or in other words a quantity proportional to the number of lines of force threading the circuit. The size of the current induced in the circuit depends on the electrical resistance of the circuit, and for the same E.M.F. it varies inversely as the resistance: it is for this reason that Faraday's formulation was in terms of the driving E.M.F. rather than the current it drives, since the E.M.F. depends only on the rate of change of flux, while the current depends on the resistance as well*. The sense of the E.M.F. depends on the sense in which the flux is changing; it always acts in such a way that the current it drives round the circuit produces a magnetic field which tries to oppose the change of flux. For instance, if the flux is decreasing, the induced current flows in such a sense as to try to prevent the decrease, by setting up a

* Actually the current depends also on what is known as the *self inductance* of the circuit, and the strict formulation would become very cumbersome if current rather than E.M.F. were used in the definition.

field in the same direction as the field which is decreasing.

An important example of how Faraday's law works is if a coil (for instance the rectangular coil of fig. 20), is rotated in a uniform magnetic field. As it rotates, the number of lines of force through the coil varies from a maximum when the plane of the coil is perpendicular to the field, to zero when it is parallel to the field. This change of flux induces an E.M.F. in the coil which can be used to drive electric current in an outside circuit if the current is led out of the coil by slipping contacts (so that the rotation can be carried on without breaking electrical contact). This example illustrates the principle of the *dynamo*, a machine which transforms mechanical power into

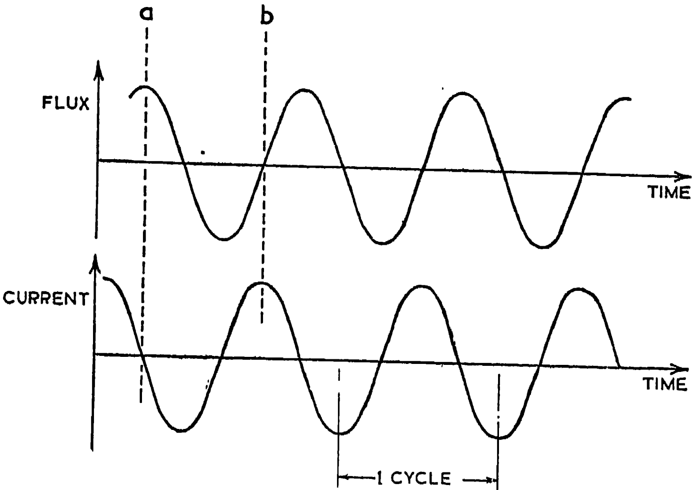


Fig. 22.—The time variation of the flux through a coil rotating in magnetic field. The current produced is proportional to the rate of change of flux, and so is zero at points like *a* where the flux is a maximum or a minimum and is largest at points like *b* where the flux is zero.

electricity. It is the means by which nearly all the electrical power used in industry and everyday life is generated.

The rate of change of flux through the coil of a dynamo is not constant, and so it produces what is known as *alternating current* (*A.C.* for short). This is illustrated in fig. 22, which shows first how the flux through the coil varies with time, and then how the current produced, which is proportional to the rate of change of flux, varies with time. It will be seen that the current goes up and down and changes direction in a smooth and regular way; the variation from one peak to the next is called a *cycle* (corresponding to one complete rotation of the dynamo coil), and the number of cycles per second is called the *frequency*. The current which is supplied by the electric light "mains" (wires which are connected to the coil of a dynamo at an electric power station) usually has a frequency of 50 cycles per second in England, and 60 cycles per second in the United States. The fact that the current is not continuous (*direct current* or *D.C.* for short) is not only not a disadvantage, but even an advantage, since many electrical devices can be constructed more simply if they are designed to work from A.C. rather than D.C. For instance, the motor of an electric clock is designed for A.C. and its accurate time-keeping depends on the constancy of the frequency, or ultimately on the constancy of the rotational speed of the dynamo which generates the current. If for any special purpose D.C. is required, it can easily be manufactured from A.C. by a device known as a rectifier, which lets the current flow only one way, and smoothes out the ripples of the A.C.

6. *Maxwell's synthesis of electricity and magnetism: "electromagnetics"*

With Faraday's discovery of electromagnetic in-

duction, the basic facts about the electromagnetic field were all there ; it was left however to the physical intuition and mathematical genius of Clerk Maxwell (who by a curious coincidence was born in 1831, the year of Faraday's discovery) to realize their far reaching implications. He generalized the results to cover cases which had not yet been studied experimentally, and combined his generalizations into a neat mathematical framework.

First of all he introduced the idea of a *displacement current*, a current which flows even in a vacuum and is associated with a changing electric field. In our discussion of Ampère's theory we always supposed that the electric current flow was continuous in an unbroken circuit, the current being the same in all parts of the circuit, but if we consider the flow of current when static electricity is discharged we have a rather different case. If a charged electric condenser (for instance, two metal plates separated by an insulating gap, as in fig. 23) is discharged by a wire, ordinary electric current flows in the wire until the plates have lost their static charge. Maxwell showed that Ampère's formulation was not logically complete unless the current in the wire was continued through the insulating gap as a displacement current, proportional to the rate of change of electric field in the gap. He assumed that the magnetic effects were due not only to the current in the wire but also to the displacement current, and more generally that there was always a magnetic field associated with a changing electric field. This suggestion was later verified by direct experiment when Rowland showed that a magnetic field was produced if a statically charged body was rapidly moved : the magnetic field was due to the rapidly changing electric field as the body moved by, and the strength of the magnetic field was just what Maxwell predicted.

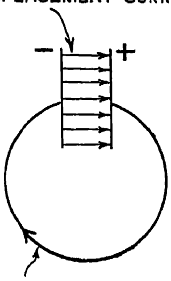


Fig. 23.—Although ordinary current stops at the plates of the discharging condenser, displacement current flows across the gap.

His second generalization was of Faraday's result. He suggested that an electromotive face was always induced by a changing magnetic field even if no wire was present along which a current could be driven. Thus, even in a vacuum, he pictured an electric field as being produced at every point where the magnetic field was changing. This idea too has been abundantly justified by experiment and we shall come across a direct application of it in the *betatron* (Chapter 7), an important tool in modern research, where a charged particle is accelerated by just such an electric field.

With these two generalizations Maxwell was able to write down four fundamental equations which, in a compressed form, describe the inverse square law for magnetism (and the fact that isolated poles do not occur), the inverse square law for electric charges, the generalized Ampère's law, and the generalized Faraday's law. These four Maxwell equations essentially sum up the properties of the electromagnetic field, and with their aid, any problem in electricity and magnetism can in principle be solved. This theory does not explain the properties of matter as, for instance, the

various degrees to which different kinds of matter can be magnetized. It accepts such facts without explanation and merely predicts their consequences. The properties of matter appear as parameters (that is to say constants describing these properties) in the equations, and it is left to the atomic theory to explain why these parameters have their particular values.

Two of Maxwell's equations involve a constant denoted by "c," and to appreciate the consequences of the theory we must say a little about this constant. To explain what it means we must consider the units used in electrical measurements. Electric charges can be measured in units based on the inverse square law in electricity (the definition of these units is quite similar to that of the unit magnetic pole). We can then measure electric current as the quantity of charge flowing past a given place per second, and we thus have what is called an *electrostatic unit* of current corresponding to the flow of one unit of charge per second. If these units of current are used, the constant of proportionality in Ampère's law is denoted by $1/c$, i.e., we can say the strength of the equivalent shell (measured in units based on the unit magnetic pole) is the current in electrostatic units divided by c.

An alternative method of measuring current is in terms of *electromagnetic units*, such that the constant of proportionality in Ampère's law is made just unity. This defines the electromagnetic unit of current as one which would be equivalent to a unit magnetic shell if it flowed round a circuit, and it is these units of current we have used up to now. We see then that c is just the ratio of the two units : there are c electrostatic units of current in one electromagnetic unit. Similarly it can be shown that there are c electromagnetic units of electromotive force in one electrostatic unit of electromotive force. If electromagnetic units of electromotive force are used, the constant of

proportionality in Faraday's law becomes just unity, while if electrostatic units are used, the constant is again $1/c$—the induced electromagnetic force is the rate of change of flux divided by c.

The practical electrical units, with which we are familiar in everyday life, are based on the electromagnetic system of units, though not identical with them. Thus the *ampere* (*amp*. for short) is one tenth of the electromagnetic unit of current and the *volt* is one hundred million electromagnetic units of electromagnetic force. These sizes of units are convenient to avoid using unduly large or small numbers in dealing with everyday electrical effects : the current taken by a strong electric lamp may be $\frac{1}{4}$ amp., while that of an electric heater may be 5 or 10 amps., or again the electromotive force of a torch battery may be 1 or 2 volts, while that of the domestic mains is usually about 200 volts. The quantity c can be measured and turns out to be very large, 30,000,000,000 (3×10^{10}) in the metric system, so we see that a unit of electrostatic current is very small indeed compared with ordinary currents measured in amperes. The electrostatic unit of electromotive force is, however, fairly large—it is equal to 300 volts.

Maxwell's four equations can be solved. If we are told that certain electric charges are present, and their positions and motions are specified at all times, it is possible from the equations to predict what electric and magnetic fields will be produced at any place and at any time. This solution, which was worked out by Maxwell himself, has very remarkable properties, for it turns out that if an electric charge is accelerated it produces wave-like electric and magnetic fields. If, for instance, a charge is oscillated over a small distance (carrying out a motion like the end of a loaded spring), then at all surrounding points oscillating electric and magnetic fields are created. By such an oscillation

we mean that the field varies with time in the manner shown in fig. 24 (similar to the way in which an alternating current varies—fig. 22); the frequency of oscillation is the same as that of the oscillating charge.

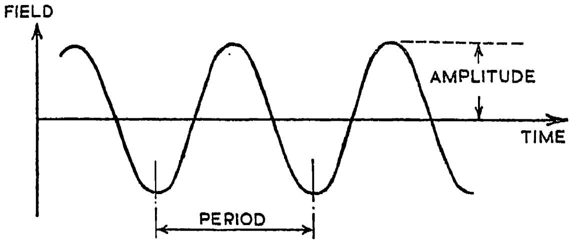


Fig. 24.—The curve shows how the field varies with time at one particular distance from a wireless transmitter.

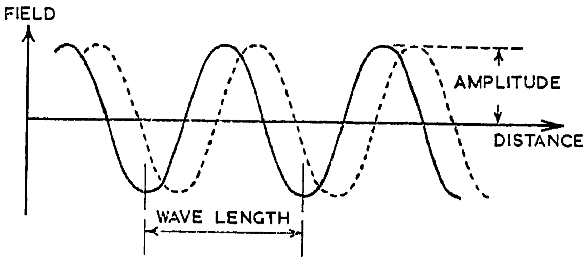


Fig. 25.—The full curve shows how the field varies with distance from the transmitter at one particular time, and the broken curve a short time later. It can be seen that the whole wave curve travels along.

This is not all, however, for at any instant the field varies from point to point also in a wave-like manner (fig. 25). The net result is that we have a continuous wave of electric and magnetic field. The *wavelength* is the distance from peak to peak in fig. 25, and just as

in the case of alternating currents, the frequency is the number of cycles per second in fig. 24. It is easy to show that the waves travel with a velocity given by frequency × wavelength, for after a time equal to one cycle the whole wave of fig. 25 will have progressed by just one wavelength. At large distances from the oscillating charge, the *amplitudes* of the electric and magnetic fields (i.e., the maximum values they attain) are equal if these fields are measured in electrostatic and electromagnetic units respectively, and the two fields are perpendicular to each other, and to the line joining the point in question to the oscillating charge. As we get further and further away from the oscillating charge source, the amplitude falls off inversely as the distance (this is not shown in fig. 25 to avoid confusion).

The most remarkable thing about these waves is that their velocity on Maxwell's theory turns out to be just "*c*," i.e., 30,000,000,000 cm./sec. or 300,000 km./sec., and this is almost precisely the velocity of light as measured by optical means. To explain this coincidence Maxwell made the ingenious suggestion that light (which was already known to be a wave motion) consists of just such electromagnetic waves. He supposed that some sort of electrical disturbance in the atoms was responsible for the emission of the light waves from hot bodies, and although the mechanism of the actual emission has only been successfully explained by modern quantum theory in the hands of Bohr and his followers, Maxwell's theory was able to correlate and explain a vast range of effects in optics. This electromagnetic theory of light, apart from some modifications introduced by quantum theory, still holds good to-day and is a remarkable example of how apparently unrelated phenomena, such as electricity, magnetism and optics, prove in fact to be merely different aspects of the same thing.

The light waves of optics are of very short wavelength, about five hundred-thousandths (5×10^{-5}) of a centimetre, but much longer waves can be produced by using man-made electric oscillations. This was first achieved by Hertz, who combined both theoretical and experimental talents. It was Hertz who first worked out a solution of Maxwell's equations, appropriate to the particular example we have described above, and later he actually produced the waves on a laboratory scale, by utilizing the oscillations which occur when an electric condenser is discharged, thus laying the foundation of modern wireless transmission. The wavelengths used for this purpose are much longer than in the case of light—they range from some cm. for use in radar to some hundreds of metres for ordinary broadcasting, but the waves are of precisely the same nature as those which transmit light, and travel with the same velocity. The equivalent of the oscillating charge of our example is the aerial of the transmitter, and the oscillating electric and magnetic fields at a distance are made to induce currents in the receiving aerial, which enable the transmission to be detected. How it is possible to transmit speech and music by this method, and many other details, cannot be gone into here, but we hope enough has been said to give some hint of how wireless works, and to show that here again magnetism is deeply involved in what at first sight seems an unrelated subject.

Although we have described Maxwell's theory as the complete answer to all electromagnetic problems, we should mention in conclusion, that Einstein's theory of relativity has actually gone a little further in knitting the basic facts somewhat closer together. In the relativity theory, the Maxwell equations can be rather more neatly expressed, so that they appear merely as four different aspects of one fundamental principle. Also certain problems which were not very satisfactorily

treated by Maxwell's form of the theory find a more logical treatment in the relativity formulation. What still remains to be done as regards field theory is to combine this relativistic electrodynamics, as it is called, with quantum theory, and perhaps to find also a connection with gravitational effects.

Chapter Three

MAGNETISM AND MATTER

1. *What is meant by magnetic properties of matter?*

IF any substance is put in a magnetic field (that is to say, close to a magnet or a coil carrying an electric current), it becomes magnetized and itself behaves like a magnet. The extent to which it becomes magnetized, measured by its magnetization (see p. 24) depends on various factors. First of all it depends on the strength of the magnetic field, usually getting stronger as the field increases, and, secondly, it depends on the kind of matter of which the substance is made. These are the main factors, but even for a given kind of matter in a given field, the magnetization may depend on the temperature, on the "state" of the matter (whether it is liquid, solid or gas) and on other circumstances which need not concern us here. In this chapter we shall give a general description of how these various factors work, and how the magnetic properties of substances are measured, while the next chapter will deal with the atomic mechanism which causes these properties and what it is that makes different substances have different magnetic properties.

Before describing the variety of magnetic properties displayed by different substances, we must first state a little more precisely what is actually meant by these properties. Let us suppose that the substance concerned has the form of a long rod, and that this rod is placed in a uniform magnetic field whose lines of force run parallel to its length. The rod will then behave like a magnet, and, as explained on p. 24, the

moment of this magnet divided by its volume is called the intensity of magnetization, or magnetization for short, of the substance; it is usually denoted by "I."

For most substances this magnetization is extremely feeble, and indeed quite special methods (see p. 64) are necessary to show that it exists at all, but for a few special substances like iron, it is very strong and easy to demonstrate. If, for instance, a piece of iron is brought near a permanent magnet, it is attracted to the nearest pole, and this is due to just the effect we are describing: the piece of iron becomes itself a magnet, and its nearest pole is attracted to the nearest pole of the permanent magnet (fig. 26). Again, if a

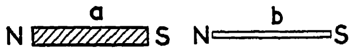


Fig. 26.—A magnet (a) produces N and S poles in the iron rod (b), the neighbouring unlike poles attract each other, and the iron is therefore attracted to the magnet.

piece of iron (such as a pin) is allowed to stick to the pole of a permanent magnet, it will attract another pin, and in this way a whole chain of pins can be built up (fig. 27). This shows that each pin has become magnetized in the field of the permanent magnet, and so is able to attract the next pin in the chain.

The fact that matter can become magnetized causes a slight complication in the definition of a magnetic field. Previously, we measured a magnetic field at any point by the force which it exerted on a unit pole at the point concerned, but what happens if the point is inside a material substance? Evidently some kind of a hole must be made into which the measuring pole can be put, and it is here that the complication arises, for it turns out that the force depends on the *shape* of the

Fig. 27.—A magnet supporting a chain of pins. Each pin acquires poles, just as in fig. 26, and produces poles in the next lower pin. Note that in practice the poles get weaker going down the chain, so eventually the attraction becomes too weak to support the weight of an extra pin.

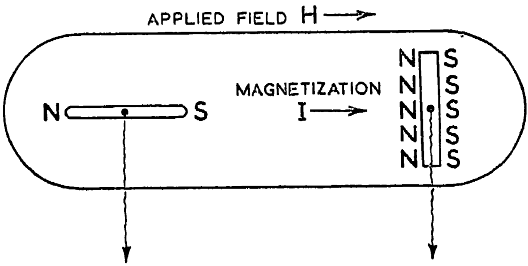


Fig. 28

A measuring pole in this long needle-shaped cavity is acted on only by H if the hole is long enough, since then the N and S poles at the ends have only a negligible effect.

A measuring pole in this disc cavity (a "pill box" slot) is acted on by H and also by the additional field $4\pi I$ of the poles induced on the faces of the slot: thus the total field here is $H+4\pi I$; this is called the magnetic induction, B.

The fields inside a magnetic material.

hole that is made. This is because the substance is magnetized, so that poles are created over the interior surface of the hole, and the field of these poles is added to the original magnetic field ; it is this additional field which depends on the shape of the hole.

Fortunately there are two limiting kinds of hole which give simple results : either a long needle-shaped hole parallel to the applied field, or a thin disc-shaped hole perpendicular to the applied field (fig. 28). In the first case, the poles on the surface of the hole occur only at its ends, and if the hole is long enough, these poles produce very little additional field at the middle of the hole, so that a measuring pole placed there measures only the external or magnetizing field. This is evidently the right kind of hole to measure the magnetizing field, since the magnetization of the substance does not alter the original field. In the second case, the induced north and south poles cover the two faces of the disc and produce an appreciable field at the centre of the hole. It can be shown that this additional contribution to the field is $4\pi I$, if I is the magnetization, and so the total force on a unit pole in this hole is $H + 4\pi I$, if H is the magnetizing field (the force on a unit pole in the needle-shaped hole). This field in a disc-shaped hole is of considerable importance as we shall see later (p. 62) and is called the *magnetic induction* ; it is generally denoted by B. We thus have the relation :

$$B = H + 4\pi I$$

which shows that the induction is a field which takes account both of the original magnetizing field (H) and the effect ($4\pi I$) of the magnetization, I, induced in the substance.

When we speak of the magnetic properties of a substance, what we really mean is the way in which the magnetization depends on the magnetizing field, or more briefly, how I varies with H. In very many substances, it is found that I increases simply in direct

proportion to H, and in this case, the constant ratio of I to H is called the *magnetic susceptibility* of the substance (usually denoted by κ). It should be noticed that since I is magnetic moment per unit volume, this susceptibility is also per unit volume, and it is sometimes called the *volume susceptibility* to emphasize this fact. If we divide κ by the mass of unit volume (the density) in grams per cc. we get a susceptibility per unit mass, called the *mass susceptibility*, and similarly if we divide κ by the number of atoms or molecules in unit volume, we get an *atomic* or *molecular* susceptibility. This concept will be useful in the next chapter where we shall be concerned with showing how the properties of single atoms and molecules cause the magnetic behaviour of the whole substance. An alternative way of describing magnetic properties (more useful for the applications, rather than the explanation of these properties) is to specify the ratio of B to H instead of I to H. This new ratio is called the *permeability* and is usually denoted by μ. Since $B = H + 4\pi I$, it follows if we divide by H that

$$\mu = 1 + 4\pi\kappa.$$

So we see that the permeability and susceptibility are simply related. If κ is very small, as is true for feebly magnetic substances, then μ is very little different from 1, while if κ is very large, as it is for iron, then μ is almost the same as $4\pi\kappa$.

2. *Paramagnetics, diamagnetics and ferromagnetics*

Broadly speaking, materials can be classified into three groups as regards their magnetic properties. The great majority of substances are only very feebly magnetic, with a susceptibility κ of only 10^{-4} or less. This small susceptibility may, however, be either positive or negative, and usually it is smaller (10^{-6} or less) if it is negative. If it is positive, the substance is said to be *paramagnetic* and the induced magnetization

has the same direction as the field, while if it is negative, the substance is said to be *diamagnetic* and the induced magnetization has a direction opposite to that of the magnetizing field. In the case of diamagnetics it follows that the induction B is less (but only very slightly less) than the field H, while in the case of paramagnetics it is greater. These two kinds of behaviour are illustrated in fig. 29, which shows the polarity of the substance when magnetized by a bar magnet; it is evident that the diamagnetic will be repelled by the bar magnet, while the paramagnetic will be attracted, though of course in both cases the force is extremely small owing to the feebleness of the induced magnetization.

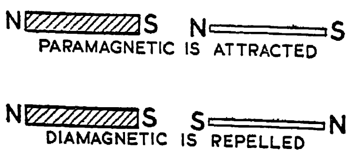


Fig. 29.—Illustrating the difference between diamagnetic and paramagnetic behaviour. Note that the N and S poles induced in such materials are very much weaker than those in iron (as in fig. 26).

A small minority of substances have a totally different behaviour and form the third group of our classification. These are the so-called *ferromagnetics* or iron-like substances: iron, nickel, cobalt, gadolinium, and various alloys or compounds usually containing one or other of these elements. Their characteristic is that they acquire a very high positive magnetization in quite small fields, so that in a sense they are paramagnetic with an unusually high susceptibility. The susceptibility depends very much on the purity and

mechanical state of the ferromagnetic, but is always of a quite different order magnitude from that of ordinary paramagnetic substances, being as high as 100,000 for very pure and unstressed iron.

This high susceptibility is not, however, the only characteristic which distinguishes ferromagnetics from paramagnetics. For para- and diamagnetics, the magnetization increases in proportion to the field even for fields as high as 100,000 gauss, but for ferromagnetics the proportional increase occurs only for very low fields. When the field is increased beyond a certain value (depending on the particular ferromagnetic concerned, but usually only a few gauss or less) the magnetization increases more slowly and eventually ceases to increase altogether ; the ferromagnetic is then said to be *saturated*. This is illustrated in fig. 30, where the magnetization I is plotted graphically against the magnetizing field H for typical materials; such diagrams are called *magnetization curves*.

Since, for a ferromagnetic, I is no longer in a constant ratio to H it is no longer sufficient to describe the magnetic properties in terms of susceptibility, and the whole magnetization curve is needed to specify the properties. This is in contrast to the para- and diamagnetics, where the magnetization curves are simply straight lines (apart from one or two exceptions which will be mentioned later), and the susceptibility, which determines the slope of the line, is sufficient specification of the magnetic properties.

It is found that for a given ferromagnetic at a given temperature, the whole course of the magnetization curve depends very much on how the ferromagnetic has been made, but the intensity of magnetization at saturation is always much the same for the same kind of substance. For instance, any piece of iron will have a saturation magnetization of about 1,600, or 1,700 gauss, but the magnetization curve by which this

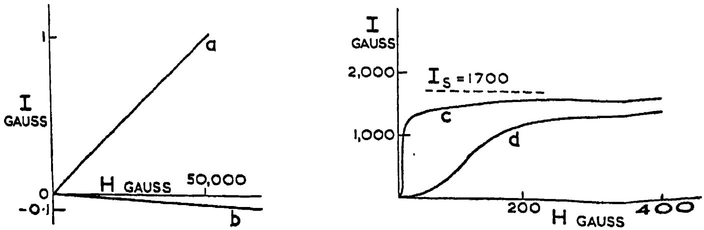


Fig. 30.—Magnetization curves of typical materials :

(*a*) A paramagnetic with volume susceptibility 2×10^{-5} ;

(*b*) A diamagnetic with volume susceptibility -2×10^{-6} ;

(*c*) A soft ferromagnetic with a maximum volume susceptibility of order 1,000 or more ;

(*d*) A hard ferromagnetic with a maximum volume susceptibility of order 10.

Note that in (*c*) and (*d*) the magnetization does not vary proportionally to the field, and that in spite of the different initial behaviour the soft and hard materials both saturate at about the same magnetization if big enough fields are used (a bigger field is needed for (*d*) than for (*c*)).

saturation is reached will depend very much on the treatment the iron has had in manufacture. If it is very pure, and has been very well annealed (very slowly cooled from the molten metal, to remove internal stresses that would otherwise exist), the magnetization curve will rise very steeply and saturation will be reached at fairly low fields (fig. 30*c*). If, however, it contains impurities and has been "quenched" (suddenly chilled from a high temperature) the initial susceptibility will be much lower (though still much more than that of a typical paramagnetic) and much higher

fields are needed to saturate it (fig. 30*d*). In both cases, however, the saturation magnetization has much the same value—about 1,600 for iron.

Another striking difference between ferromagnetics and other materials is that ferromagnetics exhibit *hysteresis*: if, after the field has been increased to some value, it is again reduced, the magnetization does not retrace the original curve. Fig. 31 illustrates typical *hysteresis cycles* in which the field is raised to saturate the ferromagnetic, then reduced to zero, then applied in the reverse direction until it again causes saturation in the new direction, then brought back again to zero, and finally again increased in the original direction. The amount of this hysteresis depends very much on the state of the ferromagnetic and is usually small for magnetically *soft* materials which have a steep magnetization curve and large for magnetically *hard* materials, which require large fields for saturation. The hysteresis is roughly specified by the *remanence* and the *coercive force*, which are indicated in fig. 31 : the remanence being the retained magnetization when the field is brought back to zero, and the coercive force the reverse field which has to be applied to bring the magnetization back to zero. It is found that as between different materials, the remanence varies rather less than the coercive force : the remanence is very roughly about half the saturation intensity for most materials, while the coercive force may vary from as little as 0·01 gauss for a very soft material to as much as 1,000 gauss for a very hard material.

These hysteresis effects are of immense technical importance since their magnitude decides whether or not the material is suitable for a particular technical application. This question will be discussed in more detail in Chapter 5, but at this point it should be noticed that it is the remanence which makes possible the existence of permanent magnets. If in fact the

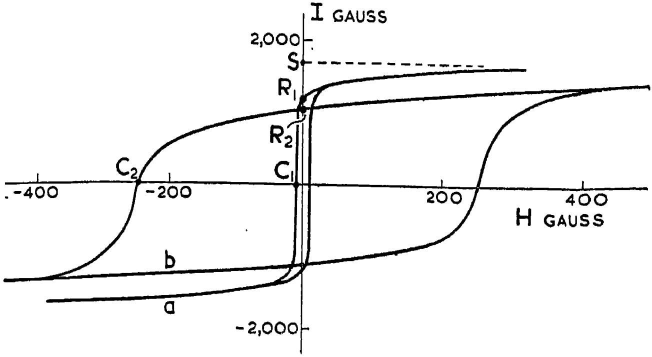


Fig. 31.—Typical hysteresis loops of a soft and a hard ferromagnetic material (the same materials as in fig 30 (*c*) and (*d*)). S represents the saturation magnetization which is much the same for both (though rather high fields would be needed to reach it for the hard material). The remanences (represented by R_1 and R_2) are not very different for the soft and the hard materials, but the coercive force of the hard material (C_2) is very much greater than the coercive force of the soft material (C_1).

ferromagnetic retains magnetization without any magnetizing field, as it does at remanence, it is a permanent magnet, and since every ferromagnetic shows hysteresis to some extent, it can always be made into a permanent magnet by first applying a magnetic field and then removing it. We shall, however, see later (p. 73) that the merit of any particular material as a permanent magnet depends even more on the coercive force than on the remanence, so that in practice only hard materials with high coercive force are of much use as permanent magnets.

So far we have dealt with the variation of I with H

for different substances, and we must now consider how these properties depend on the temperature and on the state of aggregation (i.e., whether the substance is solid, liquid, or gaseous). Most diamagnetics and some paramagnetics have a susceptibility which varies very little with temperature over the whole range in which the substance retains its particular state of aggregation. Some paramagnetics, however, and notably certain chemical compounds, known as salts, have a susceptibility which varies inversely as the *absolute temperature.** This law of temperature dependence was discovered by Pierre Curie, who, with his wife, Marie Curie, first studied radioactivity. He was the first after Faraday to make a systematic study of the magnetic properties of feebly magnetic substances, and the law is usually called after him. To illustrate *Curie's law*, consider the case of potassium chrome alum which is a typical paramagnetic salt. At 300°K (27°C.) it has a susceptibility of $2{\cdot}3 \times 10^{-5}$, while at the extremely low temperature of 1°K. (—272°C.), which can be reached by cooling with liquid helium, its susceptibility is 7×10^{-3}, or 300 times greater. At such a low temperature, even a paramagnetic begins to show saturation in fields of a few thousand gauss. (This is one of the exceptions mentioned on p. 55 to the usual proportionality.) But its saturation magnetization is rather smaller than for iron (it is about 60 gauss for potassium chrome alum), and there are no hysteresis effects.

In the case of ferromagnetics, the main effect of temperature change is to alter the saturation magnetization. As the temperature is raised, the saturation decreases until at a certain temperature called the

* On the centigrade scale this is 273 plus the ordinary centigrade temperature. For instance, on a hot day (27°C., which is just over 80°F.) the absolute temperature is 300°K. The K used to denote absolute temperature stands for Kelvin who first introduced it.

Curie point, it disappears altogether (fig. 32). Above this Curie point, which is at nearly 800 °C. for iron, the ferromagnetic becomes a paramagnetic, with a susceptibility which varies inversely, not as the absolute

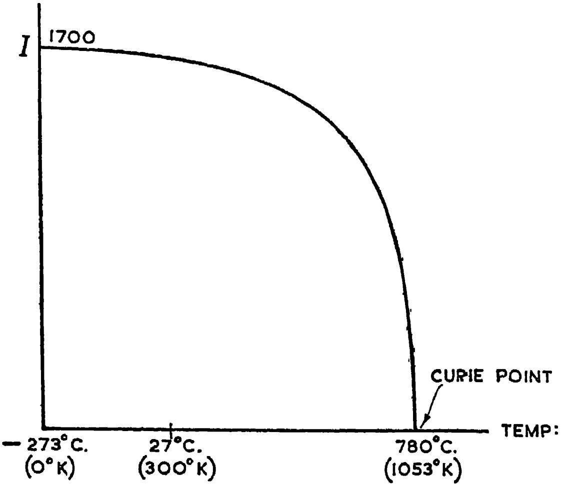


Fig. 32.—Variation of the saturation magnetization (I) of iron with temperature. The saturation magnetization disappears at the Curie point (780°C.) and at higher temperatures the iron is paramagnetic. Note that there is no very great increase in saturation however much the temperature is lowered below room temperature (taken as 27°C.).

temperature, but inversely as the temperature *difference* from the Curie point. This result is often called the *Curie-Weiss law* in honour of Curie, who first found it by experiment, and of another great French magnetician, Pierre Weiss, who first explained it theoretically (see Chapter 4).

When the state of aggregation of a substance changes, as for instance, when a gas condenses and becomes liquid, its susceptibility may change for two reasons. First, the density of the substance changes (for instance, the density usually increases about a thousand times when a gas liquefies) and so a unit volume contains a different number of molecules in the various possible states of aggregation. If the magnetization is an effect characteristic of the individual molecules, it is natural to expect that the susceptibility will be just proportional to the number of molecules per unit volume, and so it will change when the density changes with change of state. If this were the only effect, we should then expect to find the molecular susceptibility constant even when the state changed.

There is, however, another possible effect of change of state. This is if the susceptibility depends on the nature of the forces which hold the molecules of the substance together, as well as on the properties of the individual molecules. These interaction forces, as they are called, are weakened when a solid melts, and are even more weakened when a liquid evaporates into a gas, so if they play any role in determining the magnetic properties, we should expect the molecular susceptibility to change when the state changed, while if they are irrelevant there would be no change. Both cases occur in practice: for instance, solid bismuth just before it melts has a susceptibility of -9×10^{-6}, and this falls to $-0{\cdot}4 \times 10^{-6}$ when it is liquid, although there is little change of density. This is clearly a case where the susceptibility depends strongly on the nature of interaction forces between the bismuth atoms, and is greatly changed when these forces are modified by the melting of the bismuth. On the other hand, phosphorus when it melts changes its susceptibility almost exactly in proportion to its density, so we can conclude that its susceptibility is just the sum of the

effects of the separate phosporus atoms, and does not depend appreciably on their interactions.

3. *The importance of the magnetic properties of matter*

The two main laws connecting electricity and magnetism (see Chapter 2) become modified when account is taken of the magnetic properties of matter, and these modifications can be turned to advantage if strongly magnetic matter (such as iron) is used in the right way. It is, indeed, these modifications which make possible the practical realizations of such machines as the motor and the dynamo which would otherwise be little better than laboratory toys.

We have already seen that a coil of wire carrying an electric current behaves like a magnet, but if the coil is wound on a core which has strong magnetic properties, the equivalent magnet can be made much stronger. In fact, the equivalent magnet is then made up of the equivalent magnet of the current circuit together with the induced magnetism of the core. If the core is ferromagnetic (so that I is much greater than H), then the extra effect due to the core becomes the major contribution and we can get a powerful magnet without using a large electric current. This is the basis of the enhancement of the power of an electric motor (by winding its coil on an iron core) and also of the production of large magnetic fields with the expenditure of relatively little electric power. We may notice that if we have a coil, wound on a long iron rod with flat ends, the magnetic field just outside one end of the rod is made up of H due to the electric current, and the field due to the magnetization of the iron. This last contribution turns out to be just $4\pi I$, so the total effect is $H + 4\pi I$, which is just B, the magnetic induction in the iron, and may be many times larger than H, the effect of the electric current in the absence of iron. This is one example of the

practical importance of B, which may have seemed a little artificial when it was first introduced as the field in a disc-shaped cavity (p. 52).

Another important application of the magnetic induction, B, is in connection with the modification of Faraday's law brought about by the presence of material bodies. We saw in Chapter 2 that if the magnetic field was changing, an electromotive force was developed in a coil of wire, and this could drive an electric current round the wire if the circuit was closed. If the coil is wound on a core of magnetic material, this electromotive force is enhanced, for now the changing magnetic field causes also a changing magnetization of the core. It turns out that in such circumstances the electromotive force produced is proportional not to rate of change of magnetic field $\times$ coil area (as it would be without a core), but to rate of change of magnetic induction $\times$ coil area. Since in a ferromagnetic B is many times greater than H, this modification of Faraday's law is very important. If, for instance, the coil of a dynamo is wound on an iron core it becomes much more effective as a source of electric energy.

In Chapters 7 and 8 we shall describe a number of other practical applications of magnetism, and we shall see that in nearly every case, these applications utilize the enhancement of magnetic effects brought about by the use of magnetic material. Since, essentially, it is the difference between B and H which makes these enhancements worthwhile, it is evident that only ferromagnetic materials can play any serious role in technical applications. In para- and diamagnetics, the difference between B and H is so small compared with H itself, that such materials have practically no influence on the effects concerned. Why, then, have we bothered about para- and diamagnetics if they are of so little practical value? The answer to this question

provides a typical example of the way that science works. It turns out, as we shall see in the next chapter, that para- and diamagnetics, in spite of the feebleness of their magnetic properties, provide the clue to the whole mechanism of magnetism, and it would be impossible to understand the behaviour of the technically important ferromagnetics without first explaining the behaviour of para- and diamagnetics. In order to understand an effect of practical importance, it is often necessary first to study some other effect which at first sight might seem to be of interest only to the academic scientist.

4. *How the magnetic properties of matter are measured*

So far, although we have said a good deal about the various kinds of magnetic properties characterizing different kinds of materials, we have given little indication of how these magnetic properties can be measured experimentally, except to mention that this is a more difficult problem for the feeble para- and diamagnetics than it is for the strong ferromagnetics. One of the two basic methods of measurement is really a development of the simple demonstration, already described (p. 54) in which a mechanical force is observed between a magnetized material and the magnet which provides the magnetizing field. If a rod of magnetic material is put in a magnetic field, it becomes magnetized (more or less strongly according to the nature of the material), and acquires opposite poles at its two ends. If the magnetic field is exactly equal at the two ends of the rod, the two opposite poles will be acted on by exactly equal and opposite forces which will just cancel each other, leaving no net force on the rod (the two forces act along the same line if the length of the rod is parallel to the field). If, however, the field is not exactly uniform, the two opposite poles will be acted on by slightly unequal

forces and there will be a resultant mechanical force acting on the whole rod. This force will try to pull the rod in the direction in which the field gets stronger if the rod is paramagnetic, and in the opposite direction if the rod is diamagnetic ; if the force is measured, the susceptibility of the rod can be deduced.

It can be easily shown that the size of the force is given by the magnetic moment of the rod $\times$ the rate at which the magnetizing field varies in space, so the magnetic moment of the rod is obtained by dividing the observed force by the rate of field change (the *inhomogeneity* of the field). It only remains to divide the magnetic moment by the volume of the rod and by the field H itself, and we have the susceptibility, κ. How big is the force in practice? Let us consider a typical feebly magnetic material with $\kappa = 10^{-6}$; a good laboratory electromagnet will easily give a field of 20,000 gauss, and in the region near the edges of its pole pieces this field will vary at a rate of 5,000 gauss per cm. So the force acting on unit volume (1 cc) of the specimen placed in this region will be $20{,}000 \times 5{,}000 \times 10^{-6} = 100$ dynes, which is roughly 0·1 gm. weight. Actually it would not usually be practicable to use as large a volume as 1 cc, since the rate of change of field would not be very constant over such a large volume unless the electromagnet was enormously large, and in practice 0·1 cc would be the largest size of specimen which could be used, so that the force would be only 10 milligrams at most. To measure this accurately requires quite a sensitive balance, and much ingenuity has been used in devising compact and sensitive balances for this purpose.

The detailed arrangements depend very much on the circumstances of measurement, on what sort of magnet is available, on whether the measurement is to be at high or at low temperatures and so on, but a typical experimental set-up is illustrated in plate V(d). In this

case the purpose has been to measure susceptibility at the very low temperatures achieved by surrounding the specimen with liquid helium. The specimen need not be a long rod (this particular shape was mentioned only to simplify the explanation, but it is not essential) and in this set-up it is approximately spherical (it cannot be seen in plate V(*d*) because it is hidden by the magnet). The specimen is suspended from a special type of spring balance invented originally by Sucksmith in Bristol, and the whole balance has to be isolated from the outside air, which would otherwise solidify in the cold part of the apparatus and make measurements impossible. The magnet illustrated is an ordinary core-free solenoid, because for special reasons only low magnetic fields were required in this experiment,* but usually an iron-cored electromagnet, such as is shown in plate V(*a*), would be needed.

The same principle could be used to measure the magnetization of ferromagnetics, for the forces to be measured are enormously larger. If we used a field of 20,000 gauss with an inhomogeneity of 5,000 gauss per cm, a piece of iron would be already saturated, and would have a moment of 1,600 per cc. Thus the force acting on it per cc. would be 1,600 × 5,000 dynes or 8 million dynes ; this is about 8 kilograms (18 lb. weight). It is, in fact, a common experience to have a steel tool, such as a screw-driver or a pair of forceps, snatched out of one's hand when it is accidentally brought too close to a large electromagnet, and if this happens, the impact with which it hits the magnet can be violent enought to break the tool. In practice, the force method is not very convenient for measurement of the magnetic properties of ferromagnetics, and an alternative principle is generally used. Basically

* The experiment was to measure the magnetic properties of a superconductor (see p. 105), and in this case low fields are not only convenient, but essential, since high fields destroy superconductivity.

this makes use of the modification of Faraday's law, when a coil is wound on a core of the material in question, and an E.M.F. is induced in the coil by a changing magnetic field.

One common experimental arrangement is to wind two coils on a ring of the material whose magnetic properties are to be studied. If, now, a measured current is switched on suddenly in one of the coils it produces a a sudden change of field H, in the ring, and an impulsive electromotive force is produced in the second coil, which is proportional to the change of magnetic induction, B, in the material of the ring. This impulsive electromotive force can be measured by connecting the second coil to a galvanometer, which gives a sudden "kick." From the size of the kick the change of B can be deduced. By making further sudden changes of current in the first coil and measuring the corresponding changes of B, the whole B-H curve (and hence the I-H curve, such as shown in fig. 31) can be drawn out. The same method could in principle be used for feebly magnetic materials, but even with the most sensitive instruments, the difference between B and H would be too small to measure accurately, so the method is in practice suitable only for strongly magnetic substances.

The Faraday principle can be used in another way, which has certain advantages but which has not yet been fully developed to give its maximum possible sensitivity. Imagine a coil with very many turns placed in a uniform magnetic field H (say at the centre of a long solenoid—see fig. 33). If now a specimen which has a magnetic moment M in the field H is suddenly withdrawn from the centre of the coil (but always remaining in the field H), there will be a small change in the flux passing through the turns of the coil, and an impulsive electromotive force will be developed across the coil, proportional to M and to the number of turns in the coil. Just as in the previous

method, the effect of this electromotive force can be measured by the kick it gives to a sensitive galvanometer. One advantage of this method over the previous one is that it measures the magnetic moment directly, rather than *changes* of the magnetic moment (since the measurement does not require the magnetic moment to change but merely to be displaced). More-

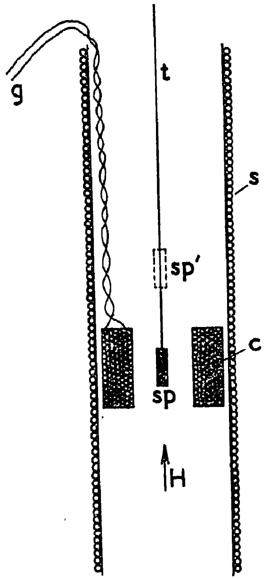


Fig. 33.—Electrical method of measuring magnetization. *c* is a coil of many turns of fine wire connected to a galvanometer by the wires *g*, and placed in a long solenoid *s*, which produces a magnetizing field *H*. The specimen *sp* is hung by a thread *t* inside *c* and when it is suddenly moved to *sp′* a sudden deflection indicating the magnetic moment of *sp* is recorded by the galvanometer.

over, in the previous method it is always changes of $B = H + 4\pi I$ which are measured, so that if I is small compared with H no increase of sensitivity will help in measuring I by itself, since the major effect will be due to H. This new method is, in fact, capable of a much greater sensitivity than the previous one and may ultimately become more sensitive and convenient than the force method.

5. *Demagnetization*

In various places we have spoken of a " long rod " of magnetic material in describing magnetic properties and the methods of measuring them. This has been partly to make the treatment simpler, but also because in some cases, the long rod shape avoids difficulties due to an effect known as *demagnetization.*

Let us return to the consideration of the force acting on a unit pole put inside a long needle-shaped cavity cut into the specimen, but, instead of a long rod specimen, let us suppose we have some other shape, say a sphere (fig. 34). The field in the cavity (the force on the unit pole) will now be due not only to the field which is applied from outside, but also to the poles induced on the outside surfaces of the specimen. This last contribution, as can be easily seen from fig. 34, acts oppositely to the magnetizing field and calculation shows that for a sphere this " back " or *demagnetizing field* is $\frac{4}{3}\pi I$. If we call the applied field H_a (this is the field that would exist if the specimen were absent), the field in the cavity is

$$H = H_a - \tfrac{4}{3}\pi I$$

It is this cavity field which decides what magnetization I the specimen will acquire, and since we have seen that for a ferromagnetic I is usually much larger than H, we shall have approximately that $\frac{4}{3}\pi I$ is equal to H_a. In other words if the substance is strongly magnetic the magnetization of a sphere, produced by a given

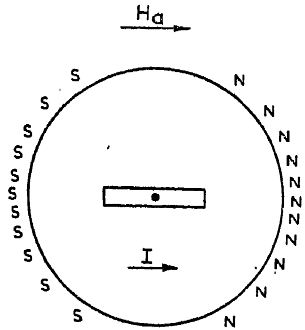


Fig. 34.—When a sphere is placed in a magnetic field H_a the poles induced on its surface cause a back or demagnetizing field, which is $\frac{4}{3}\pi I$, so that the field H measured in a long needle-shaped cavity is $H = H_a - \frac{4}{3}\pi I$.

applied field, is not appreciably determined by the magnetic properties, but is roughly just $3/4\pi$ times the applied field. If the shape is not spherical, the factor $\frac{4}{3}\pi$ in the demagnetizing field must be replaced by some other factor, depending on the shape. This factor gets smaller as the shape becomes elongated in the field direction, and would vanish for an infinitely long rod. It is for this reason that we have chosen long rod shapes in our arguments, since for a sufficiently long thin rod the demagnetizing field is negligible. It is fairly obvious why the demagnetizing field vanishes for a long thin rod, for in this case the induced poles are at the ends of the rod, and are so far away from the cavity that they have little effect. If the specimen, however, becomes flattened to oppose a large surface area across the field, the factor increases above $\frac{4}{3}\pi$. Actually, it has its largest possible value (which is 4π) for a disc-shaped specimen with its plane perpendicular to the field. If the material in question is only feebly

magnetic, with I much smaller than H, it is evident that demagnetizing effects are of no importance, since H is practically identical with H_a, but with ferromagnetics the demagnetizing effect is all important.

In measuring the magnetic properties of ferromagnetics, demagnetizing effects must always be eliminated, for to get at the basic properties of the material we must know how I varies with H, rather than with H_a. As already explained, the demagnetizing effect can be made small by using a long rod specimen, but a ring specimen with a field running round it is even more satisfactory, for there are no ends at all in a ring on which poles can form and produce a demagnetizing field. In most measurements rings are in fact used, though in special cases long rods or flat bars can be used and a small demagnetizing correction applied.

Another example of the practical importance of demagnetization occurs when we wish to know the magnetic moment of some large mass of iron. During the war, for instance, it was often essential to estimate the magnetic moment induced in an iron bomb or a ship (also mostly iron) by the earth's magnetic field (see Chapter 8). Such bodies have usually a shape which causes a large demagnetizing effect, and the magnetic moment therefore depends almost entirely on the shape of the iron, and hardly at all on the detailed magnetic properties of the iron. This enables the magnetic moment to be estimated without bothering about the quality of the material of which the bomb or the ship is made (provided always that it is a sufficiently strongly magnetic material).

Demagnetization is also important in the design of permanent magnets. In a permanent magnet there is no applied field at all, so the cavity field is just the demagnetizing field alone. Suppose, for instance, we had a bar magnet of length l with pole strength m. The demagnetizing field at its centre would be $2m/(\frac{1}{2}l)^2$

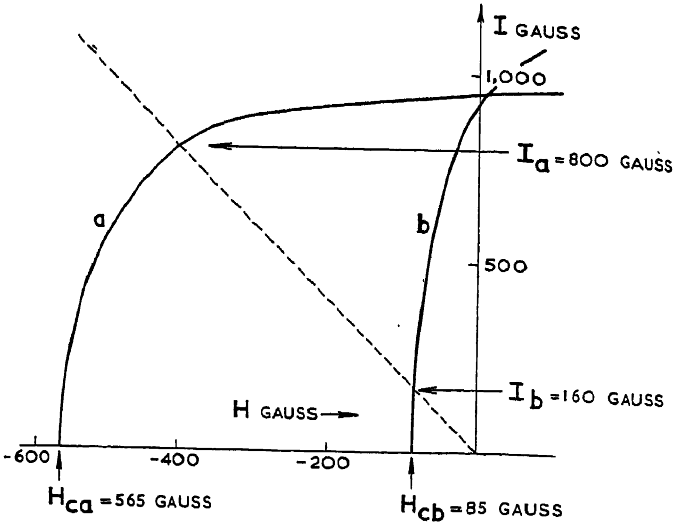


Fig. 35.—If a permanent magnet is made of the shape and size discussed in the text, its magnetization will depend very much on the properties of the material, owing to the demagnetizing effect of its poles. The magnetization is given by the intersection of the broken line, along which $H = -\frac{1}{2} I$, with the appropriate curve. Thus if the material *a*, with a high coercive force (565 gauss), is used, a much better magnet is produced than with material *b* which has a lower coercive force (85 gauss). Although the remanences are practically the same (about 950 gauss) the *a* magnet has a magnetization 800 gauss, while the *b* magnet is 5 times weaker with 160 gauss. The *a* curve is typical of good modern alloy materials such as "Alcomax," while the *b* curve is that of tungsten steel, the best material available about 30 years ago. (See Chapter 5.)

or $8m/l^2$. Its magnetic moment would be ml and so its magnetization would be $I = m/A$ if its area of cross-section was A. We can therefore write the demagnetizing field as $8AI/l^2$ (notice that as we might expect, the demagnetizing field is smallest for a long thin magnet). Now let us suppose the material of the permanent magnet has a characteristic magnetization curve which is either *a* or *b* of fig. 35, then if the magnetization is to be equal to I for a " back " field of $8AI/l^2$ only one value of I is possible for a given magnetization curve.

In fig. 35, this value of I is shown for a particular numerical example with $A = 1$ sq. cm. and $l = 4$ cm., so that the back field is $\frac{1}{2}I$. It is evident that the value of I obtained depends very much on the coercive force of the material, and even for the same remanence a much stronger magnet could be made of material *a* (high coercive force) than of material *b* (low coercive force). We can now see why coercive force as well as remanence is so important in deciding the suitability of a given material for making permanent magnets. If the permanent magnet were a closed ring, with no demagnetizing effects at all, only the remanence would matter, for then there would be no cavity field at all, but such a magnet would be of little use for most purposes, since it would produce no external field. We have given only a simple example of the importance of shape, but similar considerations apply to more complicated shapes (such as a horse-shoe magnet), and the whole art of permanent magnet design is based on this demagnetization idea. We shall see later (Chapter 5) how the development of special alloys, with very high coercive force and remanence, has made it possible to design permanent magnets which are as superior to the lodestone of Gilbert's day as is the modern steam engine to Watt's original model.

Chapter Four

WHY MATTER IS MAGNETIC

1. *The structure of matter, atoms and molecules*

IN order to understand why matter becomes magnetized in a magnetic field, and why different kinds of matter behave in the various ways described in the last chapter, we must first explain how matter is made up of atoms and molecules and how the atoms and molecules themselves are built up of even smaller bricks—electrons and nuclei. The structure of matter is a vast and fascinating subject, and a whole book would be needed to describe it in any detail. Fortunately, however, we need only some of the simplest concepts to explain magnetism, and these can be outlined in only a page or two.

The chemists have shown that there are 94 different chemical *elements* ranging from the lightest, hydrogen, to the heaviest, plutonium.* All matter is made up of these elements either separately or in chemical combination with each other. When two elements combine, they always do so in definite proportions by weight, and moreover these proportions can be expressed in such a way that each element has a characteristic number. For instance :

2 × 1 grams of hydrogen and 16 grams of oxygen combine into 18 grams of water.

1 gram of hydrogen and 35 grams of chlorine combine into 36 grams of hydrochloric acid.

* It was the recent research work in connection with the atomic bomb that revealed the existence of neptunium (the 93rd) and plutonium (the 94th, the material of the atomic bomb which destroyed Nagasaki), and also that there may be one or two still higher elements which are unstable.

35 grams of chlorine and 2 × 16 grams of oxygen combine into 67 grams of chlorine dioxide.

This suggested that every element is made up of its own kind of atoms, and that each kind of atom has a weight characteristic of the element which it makes up. For instance, if we suppose that an oxygen atom weighs 16 times as much, and a chlorine atom 35 times as much, as a hydrogen atom, the examples just given find a simple explanation. In fact, we can say that two hydrogen atoms combine with one oxygen atom, making one water molecule (a *molecule* is a combination of a few atoms), one hydrogen atom and one chlorine atom combine to make one hydrochloric acid molecule, and one chlorine and two oxygen atoms combine to make one chlorine dioxide molecule.

It will be noticed that this sort of chemical approach gives no idea how big the atoms are, but only indicates the ratios of weights of different atoms. The chemists therefore introduced the concept of atomic weights to measure these ratios; calling the *atomic weight* of hydrogen 1, the atomic weight of oxygen is 16 and of chlorine 35. The heaviest atomic weight, that of plutonium, is 250. We can also speak of *molecular weights* on this scale: 18 for water, 36 for hydrochloric acid, and so on. Sometimes also two atoms of the *same* element combine to make a molecule, because the atoms have an attraction for each other. Thus ordinary hydrogen gas is always made up of molecules each built of two hydrogen atoms, and ordinary oxygen is always made up of molecules each again built of two oxygen atoms. We can therefore say that the molecular weight of hydrogen is 2 and of oxygen, 32.

All matter, then, is made up either of atoms or of molecules, which are simple groups of atoms. How are these atoms or molecules held together in the bulk of a substance? This depends very much on the state of the substance. In a gas, the atoms or molecules

are very loosely held together and we can picture them as in rapid motion, flying about in all directions and constantly colliding with each other ; the violence of this random motion becomes greater if the gas is heated, and less if the gas is cooled. If the substance is a liquid, its atoms and molecules are much more compactly packed together—that is why a liquid is more dense than a gas and occupies less volume for the same mass—but they are still moving about at random. Finally, in a solid, the atoms or molecules become regularly arranged in a sort of lattice framework, and no longer move about freely. In fact, in a solid, the forces between atoms hold them in fairly definite and regularly arranged positions and they can only vibrate about these fixed positions. If the regular arrangement of the atoms or molecules is preserved over fairly large distances, we get what is called a *crystal*, and it is, for instance, the regular arrangement of the water molecules which is responsible for the beautiful pattern in snowflakes, which are just crystals of ice.

We can picture the transitions between the various states of aggregation in the following way. If a solid is heated, its atoms or molecules vibrate more and more violently until, at a certain temperature, the binding forces are no longer strong enough to hold the regular arrangement together. The solid then melts, and the regular arrangement is destroyed, but the molecules are still packed fairly compactly. At a still higher temperature, the motions of the molecules become so violent that even this irregular packing becomes impossible, and the liquid boils and turns into a gas, with the molecules flying about with much greater freedom.

How big are the atoms and molecules themselves? It is only in the course of the last fifty years that the answer to this question has become available. We

cannot explain here how the answer has been found, but it turns out that the atoms are very small indeed: there are 6×10^{23} (6 with 23 noughts after it) hydrogen atoms in 1 gram of hydrogen, and each hydrogen atom is only about one hundred millionth (10^{-8}) of a cm. in size. Other atoms are of course heavier (in proportion to their chemical atomic weights) and somewhat larger in size (but not so much larger). The question of the weight and size of atoms led on to the question of how the atoms themselves are constructed, and the pioneer work of J. J. Thomson, Rutherford and Bohr has given a fairly complete answer to this question too.

The atoms consist of a number of minute negatively electrically charged particles called *electrons* and a positively charged *nucleus* which contains most of the mass of the atom. The electrons weigh very little, each one weighing only about 1/2,000 part of the weight of a hydrogen atom, but they are very important, nevertheless, on account of the electric charge they carry. The atom as a whole is electrically neutral and so the positive charge of the nucleus just balances the negative charge carried by the electrons. The number of electrons in an atom (or what is equivalent, the positive charge of the nucleus) decides what kind of an atom it is, and it turns out that this number (called the *atomic number*) increases by one as we go from one chemical atom to the next in order of atomic weight. Thus hydrogen (atomic weight 1) has one electron, helium (atomic weight 4) has two electrons, and so on up to plutonium (atomic weight 250) which has 94 electrons.

The nucleus, although very important in itself (it was the investigation of the structure of the nucleus, started by Rutherford, which led to such startling developments as the use of atomic energy), plays little part in determining magnetic properties, so we need not concern ourselves with it here. We must, however,

consider how the various electrons behave within an atom, for it is they that determine the magnetic properties.

Since opposite electric charges attract each other, we might expect the negative electrons to be sucked into the positive nucleus; Rutherford and Bohr supposed that this is prevented from happening on account of rapid motion of the electrons round the nucleus. If in fact the electrons revolve round the nucleus, in the same sort of way as the planets revolve round the sun, the force of attraction (an electrical force in the case of the atom, but a gravitational one in the case of the solar system) could be just balanced by the centrifugal force of repulsion, due to the rotation. We need not go into the detailed mechanics of this electronic orbital motion, which was first worked out by Bohr with the help of the quantum theory (although we shall have to return to it a little later) but the important point is the picture it provides of the atom as a kind of solar system, with its nuclear sun, and its electron planets revolving in orbits whose size is roughly the size of the whole atom. In a molecule made up of several atoms, there will be several nuclei, and the orbits will be more complicated, no longer strictly tied to one or other of the nuclei, but fortunately we shall not need the details of this structure for our explanation of magnetism.

2. *Langevin's theory of para- and diamagnetism*

For the present all we shall need of the picture we have just given of the atom, is the idea that it contains electrons moving in orbits round the nucleus. Now, an electron moving in an orbit behaves just like a small turn of wire carrying a current, and so must have a magnetic moment equal to the area of the orbit multiplied by the equivalent current (this current is the electron charge divided by the time it takes to go

round the orbit). If there were only a single electron in the atom (as in the hydrogen atom), the whole atom would then have a magnetic moment, but when there are several electrons, the magnetic moments of their separate orbits must be added up vectorially (taking account of their directions) and if the orbits lie in various planes, they may just annul each other and leave the whole atom with no resultant magnetic moment. This would happen, for instance, if there were two electrons going round equal orbits in opposite directions: one clockwise and the other anti-clockwise. Alternatively, the magnetic moments of the various orbits may add up to give some net magnetic moment to the whole atom.

We have then to consider two possible cases (and this is just what Langevin did in his theory of para- and diamagnetism, though without such a detailed model of the mechanism): either the atom as a whole has a net magnetic moment, or it has none, but in either case it is made up of electrons rotating in orbits. Even in the first case, when each atom can be thought of as a small magnet, the substance as a whole would not have any magnetic moment if no magnetic field were applied, because the directions of the separate atomic magnets would be pointing quite at random, and so on the average would not add up to give any net magnetization (remember that these moments must be added vectorially, just as the moments of the separate orbits were vectorially added to give the atomic moment).

What happens, now, if a magnetic field is applied to the substance? If each atom is a small magnet, we might expect, at first sight, that the field would immediately turn each atom, like a compass needle, to point its magnetic moment in the field direction. If this were to happen, the substance would at once have a huge magnetic moment in the field direction, and

this magnetization would not increase any further if the field were increased (something like the saturation of a ferromagnetic). Actually, however, the moment is usually small, and increases proportionally to the field. The fallacy in the argument is that we have neglected to take account of the thermal agitation of the atoms. We have, in fact, already mentioned that the atoms are not to be thought of as billiard balls lying peacefully at rest, but rather as billiard balls constantly being stirred up by an energetic snooker player. The detailed nature of this agitation depends on whether the substance is a solid, liquid, or gas, but in every case its effect is that it tends to maintain the directions of the magnetic moments entirely at random. This " stirring-up " tendency is the stronger the higher the temperature, for the detailed theory shows that the violence of the thermal agitation is proportional to the absolute temperature.

When a magnetic field is put on, it is true that it tries to twist each atomic magnet into its own direction with a twisting force proportional to the field strength, but this twisting is strongly counteracted on the average by the tendency of the thermal agitation to keep the directions at random. The importance of " on the average " should be noticed, for in detail the process is more complicated: here and there an atomic magnet will turn fully into the field but soon afterwards will be buffeted by the thermal agitation into a different direction. It is only the average effect that can ever be observed, because the number of atoms is so huge, and fortunately this average effect can be worked out without having to consider the more detailed picture. A whole branch of physics called *statistical mechanics* was developed by Maxwell and Boltzmann in the latter half of the 19th century to deal with this kind of " average " problem and, Langevin in 1905, applied the methods of statistical mechanics to this particular

magnetic problem. We cannot give the detailed derivation of his theory, but from what has been said we might expect the magnetic moment of the whole substance (the " average " effect of all the atoms) to increase with the field and with the size of the individual atomic magnetic moment, and to decrease with the temperature.

This indeed proves to be the case : the magnetization I in a field H is given by

$$I = \frac{n\mu^2 H}{3kT}$$

where n is the number of atoms in a unit volume, μ is the magnetic moment of each atom, T is the absolute temperature and k is known as *Boltzmann's constant*—a constant which is fundamental in statistical mechanics and measures the violence of thermal agitation. Numerically k is about $1{\cdot}4 \times 10^{-16}$ ergs per degree (the *erg* is the unit of energy). It should be noticed that this theoretical result already explains some of the experimental results described in the last chapter in as far as it predicts a paramagnetic magnetization proportional to the field, and inversely proportional to the absolute temperature, just as Curie found in his experiments. The size of the susceptibility predicted by Langevin obviously depends on the size of μ, the atomic magnetic moment, but it will be convenient to discuss this a little later.

What about the diamagnetics : how is their behaviour to be explained? Langevin supposed that these are the substances in which the atoms have no net magnetic moment ($\mu = 0$), on account of the magnetic moments of the separate orbits just annulling each other. At first sight it might seem that in this case the substance would be magnetically neutral, and that if a magnetic field were applied no magnetization would result, but actually even with magnetically neutral atoms a small effect occurs within each orbit, which causes the observed feeble diamagnetism.

If we think again of an electron orbit as a small turn of wire carrying a current, it becomes liable to Faraday's law of induction, and when a field is switched on a momentary electromotive force will be induced, which tries to produce a magnetic field *opposite* to the field being switched on. This "back" E.M.F. causes a slight change in the speed of the electron in its orbit, and so the magnetic moment of the individual orbit changes slightly. The extra contribution is always such as to *oppose* the field that is applied, or in other words it is a *negative* magnetic moment, and even though the main parts of the orbital magnetic moments may cancel out, these negative contributions add up and produce a slight diamagnetic effect. Notice, incidentally, that this diamagnetic effect should occur even if the main magnetic moments of the orbits do not annul each other (producing the temperature dependent paramagnetism just described). We did not take account of it in explaining paramagnetism to avoid complicating the discussion, and actually our neglect is justified in practice, because when the paramagnetic effect occurs due to orientation of atomic magnets it is nearly always much larger than the diamagnetic effect, so that little error is made by forgetting the diamagnetism altogether.

The diamagnetic effect is not difficult to estimate. All we have to do is to calculate the change of speed of the electron in an orbit caused by applying a field. The induced E.M.F. when a field changes is given by area $\times$ rate of change of field. The mechanical force with which this E.M.F. acts on the electron is E.M.F. per unit length of orbit $\times$ electronic charge, and the acceleration is force divided by mass. Putting all this into symbols (e=electronic charge, m=electronic mass, A=orbit area, l=length of orbit)

$$\text{acceleration} = \frac{eA}{ml} \times \text{rate of change of field}$$

Now acceleration is just rate of change of velocity, so the net *change* of velocity when the field rises from zero to H is given by eAH/ml.

The magnetic moment of an orbit is eAv/l (where v is the velocity) since l/v is the time taken to go once round the orbit, and hence the diamagnetic effect due to one orbit is the change in this magnetic moment, which is

$$M = \frac{e^2A^2H}{ml^2}$$

But if r is the radius of the orbit $A = \pi r^2$ and $l = 2\pi r$ so our result reduces to

$$M = \frac{e^2r^2H}{4m}$$

When the effects from all the orbits are added together, the net result if the directions of the planes of the orbits are taken into account, comes out to be a magnetic moment per atom :

$$\frac{e^2 \times \text{[sum of the } r^2 \text{ of the various orbits]} \times H}{6m}$$

As we have explained, this is a diamagnetic moment and always occurs whether or not the atom as a whole has a magnetic moment without a magnetic field. This diamagnetic moment is proportional to the field H, and since the orbit sizes do not depend on temperature (nor of course do e and m), it produces a diamagnetism which is the same at all temperatures. This again is very similar to what is found experimentally. The numerical value of the diamagnetic susceptibility can be estimated from our formula, for we know that r is about 10^{-8} cm., e is about $1{\cdot}6 \times 10^{-20}$ electromagnetic units, and m is about 10^{-27} grams. Putting in these numbers we find for the diamagnetic susceptibility per atom (atomic moment divided by the field), taking a typical case, such as sulphur, which has 16 electron orbits (atomic number 16)

$$(1{\cdot}6 \times 10^{-20})^2 \times 16 \times 10^{-16}/6 \times 10^{-27}$$

or roughly 7×10^{-29}. Now in sulphur there are about $1{\cdot}6 \times 10^{22}$ atoms per cc, so we find for the volume susceptibility of sulphur

$$\kappa = 7 \times 10^{-29} \times 1{\cdot}6 \times 10^{22} = \text{roughly } 10^{-6}$$

This is just about the value found experimentally, and so we have our first example of how an experimentally determined magnetic susceptibility is accounted for by its atomic structure. Actually the good agreement is rather an accident, because we have taken only a very rough value for r^2 and moreover we have not explained why the sulphur atom has no net magnetic moment of its own (that is to say why sulphur is not paramagnetic).

To sum up, the prediction of Langevin's theory is that the susceptibility per atom should be

$$\frac{\mu^2}{3kT} - \frac{e^2 \times [\text{sum of the } r^2 \text{ of the various orbits}]}{6m}$$

The minus sign comes in because the second term represents a diamagnetic effect, and the first term only occurs when the separate orbital magnetic moments do not annul each other. We shall see in the next section that when the first term does occur, it is usually much bigger than the second and so the substance as a whole is paramagnetic and obeys Curie's law ; when the first term is absent (as we have assumed in our example, sulphur) the substance is diamagnetic and its volume susceptibility is usually 10^{-6} or less.

3. *What determines the size of an atomic magnetic moment?*

We were able to estimate the magnitude of diamagnetic susceptibility without knowing any details of the mechanics of orbits beyond the orbit sizes, but to estimate the size of paramagnetic susceptibilities we must go a little deeper into Bohr's picture of atomic structure.

If we consider a single orbit, its magnetic moment μ is given by electron charge $\times$ orbit area $\times$ length of orbit divided by orbit velocity ($\mu = eAv/l$ as on p. 83), and we must consider what determines v. Bohr showed that the *angular momentum* of an orbit, which is defined by mass $\times$ velocity $\times$ radius, is always a simple multiple of a fundamental constant, or *quantum* denoted by $\hbar$ and known as Planck's constant of action Its value is about 10^{-27} erg-seconds. If then we consider an orbit in which the angular momentum has just a single quantum of action, we have that

$$mvr = \hbar$$

and so

$$\text{Moment} = \frac{eA}{l} \times \frac{\hbar}{mr}$$

Putting $A = \pi r^2$ and $l = 2\pi r$ this gives

$$\text{Moment} = \frac{e\hbar}{2m}$$

In Bohr's theory this becomes a kind of fundamental unit, and the magnetic moment of an orbit should be just a simple multiple of it. This unit is called the *Bohr magneton*, and its numerical value is easily obtained from our formula ; it is roughly

$$\frac{1{\cdot}6 \times 10^{-20} \times 10^{-27}}{2 \times 10^{-27}}$$

or in round numbers 10^{-20}.

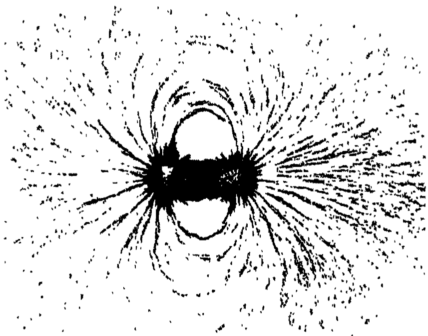
When the effect of all the various orbits in an atom are added up, the result is usually a net atomic moment of just a few Bohr magnetons. Even though there may be 50 or more orbits concerned, the effects of many of the orbits cancel each other because their moments point in opposite directions, and it is only the odd few which add up to give the net magnetic moment. If we take for a typical case $\mu = 5$ Bohr magnetons, or in other words $\mu = 5 \times 10^{-20}$, we can estimate the size of the first term in Langevin's formula.

Taking T as 300° K (27° C.), and putting in the value of Boltzmann's constant $k = 1{\cdot}4 \times 10^{-16}$, we find

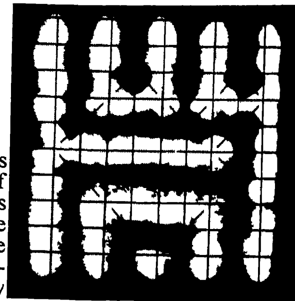
$$\frac{\mu^2}{3kT} = \frac{(5 \times 10^{-20})^2}{3 \times 1{\cdot}4 \times 10^{-16} \times 300} = 2 \times 10^{-26} \text{ per atom.}$$

If we take a typical substance in which there are 10^{21} magnetic carriers per cc., we find a volume susceptibility $\kappa = 2 \times 10^{-5}$ which is indeed the sort of value which is found experimentally for a paramagnetic which obeys Curie's law. Notice that it is something like twenty times larger than the diamagnetic term, so it is indeed reasonable to neglect the diamagnetic effect when there is a paramagnetic effect present as well.

It seems, then, that Langevin's theory is able to account for a good many of the experimental facts in general outline, and even to some extent numerically. As far as we have gone, it seems that magnetism is entirely due to the motion of the electrons within atoms of matter, but this is not the whole story. It turns out that if the atomic magnetic moments are evaluated by comparing Langevin's formula with the experimentally measured susceptibilities, the values do not generally come out to be exactly what we should expect from considering the orbital motion of the electrons. It is true that these moments always come out to be a few Bohr magnetons as we should expect, but not an exact number (1, 2, 3, etc.) as might be expected. This puzzled the atomic theoreticians a good deal and it was only in the late nineteen twenties that the reasons for this became clear. It turned out that Bohr's original orbit picture of the atom was a little too simple, and a new kind of quantum mechanics developed by Schrödinger, Heisenberg, Dirac, and others, showed that the value of μ need not be a simple multiple of a Bohr magneton, but should usually be a more complicated multiple such as square root of the

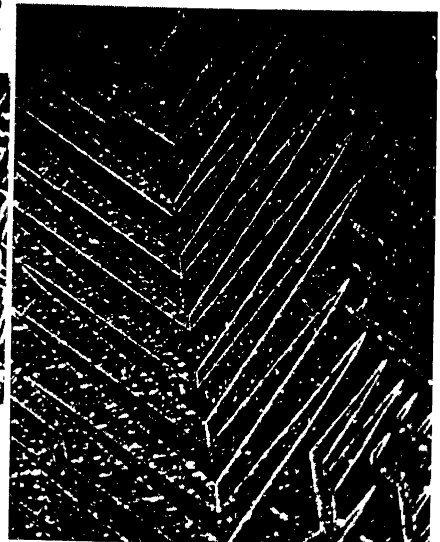


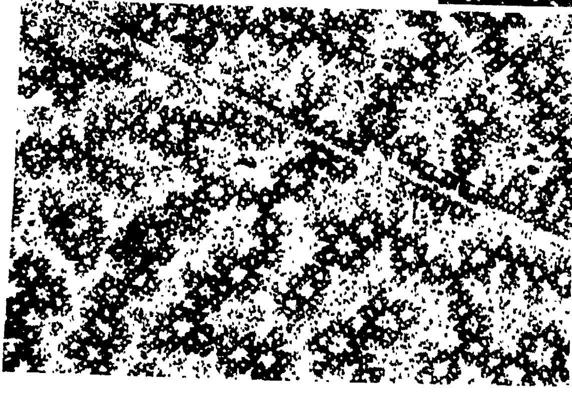
(*a*). Iron filings sprinkled round the bar magnet (about $1\frac{1}{2}''$ long) produce a rough map of the lines of force (compare fig. 4, p. 17).



(*b*). Elmore's model of domains (compare (*c*)). The black patches show where the ferromagnetic powder has settled on the array of 100 permanent magnets (each is a $\frac{1}{2}''$ cube) (p. 109).

(*c*). Ferromagnetic powder settles on the (cube) face of a mechanically polished single crystal of iron-silicon in a maze-like Bitter pattern. The whole picture is only about $\frac{1}{4}$ mm. across (p. 109).





Above: (*d*). The Bitter pattern on an electrolytically polished iron-silicon crystal face is rather like a fir tree and very different from (*c*). In this case the white lines show where powder has settled. The picture is $\frac{1}{2}$ mm. across (p. 110).

Left: (*e*). The Bitter pattern on a cobalt crystal. The picture is $\frac{1}{2}$ mm. across (p. 109).

(*a*). William Gilbert (1540-1603) showed that the earth was a magnetized sphere (p. 135).

(*b*). Hans Christian Oersted (1777–1851) discovered the magnetic effect of an electric current (p. 27).

(*c*). André-Marie Ampère (1775–1836) produced a clear quantitative formulation of the magnetic effects of an electric current (p. 27).

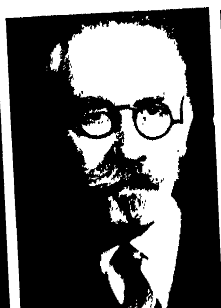
(*d*). Carl Friederich Gauss (1777–1855) developed the mathematical science of magnetostatics (p. 15).

(*e*). Michael Faraday (1791–1867) showed that a changing magnetic field produced electric effects, and made many other important magnetic discoveries (p. 38).

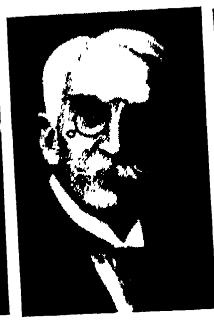
(*f*). James Clerk Maxwell (1831–1879) developed the mathematical formulation of the connections between electricity and magnetism, which later led to the discovery of radio (p. 41).

(*a*). Lord Rutherford (right, 1871–1937) talking to Sir J. J. Thomson (1856–1940), whom he succeeded as Cavendish Professor of Physics in Cambridge. They were responsible for a great part of our present understanding of the structure of matter (p. 77).

(*b*). Pierre Curie (1859–1906) showed that paramagnetic susceptibility increased inversely as the absolute temperature (p. 59).



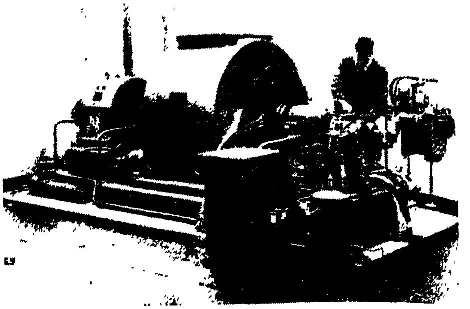
(*c*). Paul Langevin (1872–1946) explained Curie's Law in terms of the structure of matter (p. 78).



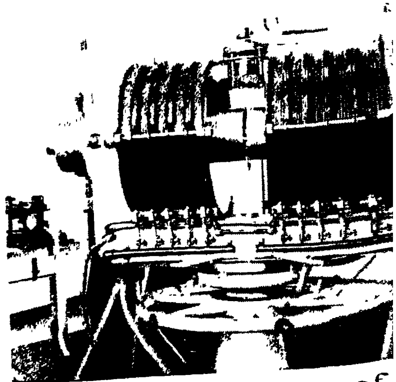
(*d*). Pierre Weiss (1865–1940) extended Langevin's theory to explain ferromagnetism, and introduced the idea of domains (p. 96).

(*e*). Pieter Zeeman (1865–1943) discovered the change of wavelength of light caused by emission in a magnetic field (p. 153).

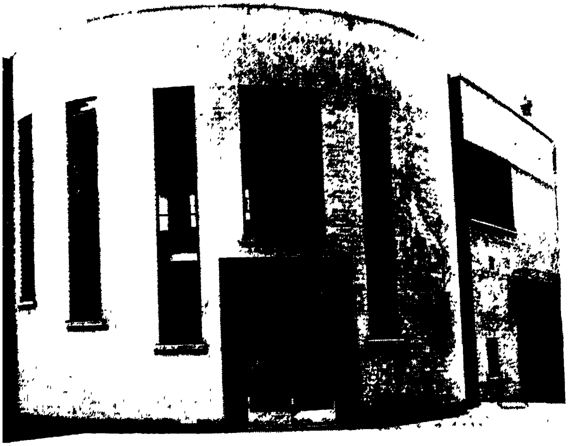
A MAGNETIC LABORATORY



(*b*). The special dynamo which Kapitza developed for momentarily producing a huge magnetic field in a coil. The complicated switch gear is in the foreground (p. 159).

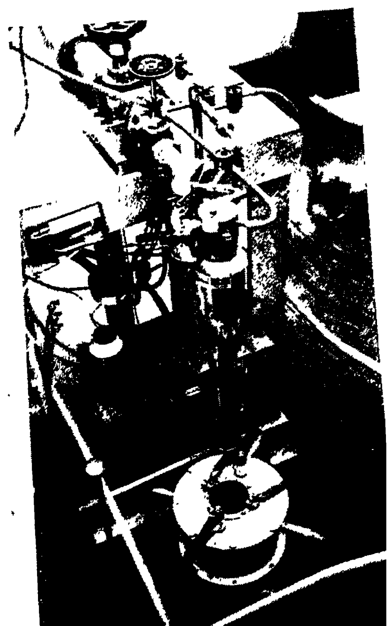


(*a*). A Weiss electromagnet in one of rooms. The coils are hollow tubes th cooling water is passed. The whol about 4 feet across (p.162).

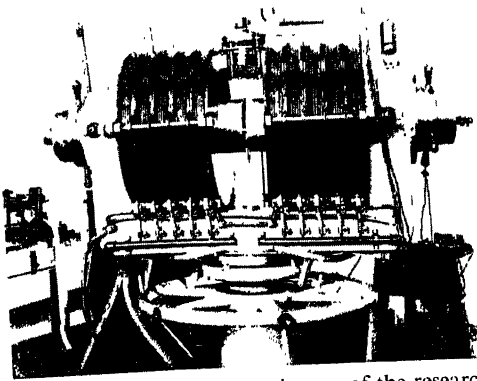


Above: (*c*). The main entrance of the laboratory. The crocodile was a nickname for Lord Rutherford whose booming voice could often be heard before he was seen, like the crocodile in Peter Pan who swallowed an alarum clock.

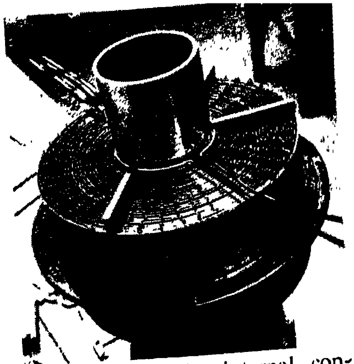
Left: (*d*). The main hall of the laboratory with the dynamo visible at the far end. The dynamo has since gone to Moscow and extra research rooms for adiabatic demagnetization have taken its place (p.160)



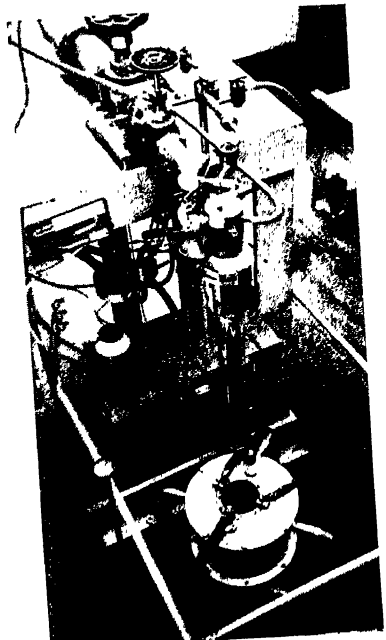
(*e*). Adiabatic demagnetization. The water-cooled solenoid (a smaller version of (*b*)) has just been lowered and the paramagnetic salt inside the apparatus has cooled to about 0.01°K (p. 178).



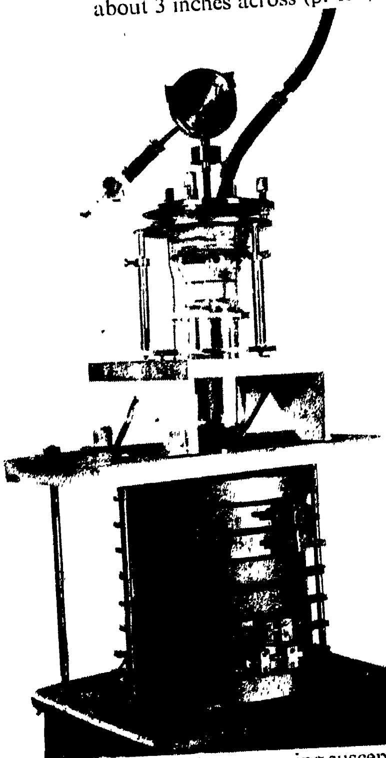
(*a*). A Weiss electromagnet in one of the research rooms. The coils are hollow tubes through which cooling water is passed. The whole magnet is about 4 feet across (p.162).



(*b*). Showing the internal construction of Ashmead's water-cooled solenoid. The hollow tube in which the field is produced is about 3 inches across (p. 159).



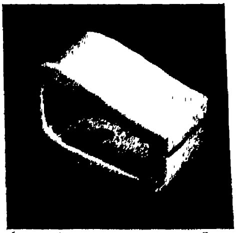
(*c*). Adiabatic demagnetization. The water-cooled solenoid (a smaller version of (*b*)) has just been lowered and the paramagnetic salt inside the apparatus has cooled to about 0.01°K (p. 178).



(*d*). A Sucksmith balance for measuring susceptibi The force on the specimen distorts the metal rin the circular case at the top, tilts the mirrors f to it, and so deflects a beam of light (p. 66).

(*b*). A small "Alcomax" horse-shoe magnet; the keeper is just over 1 in. long (p. 129).

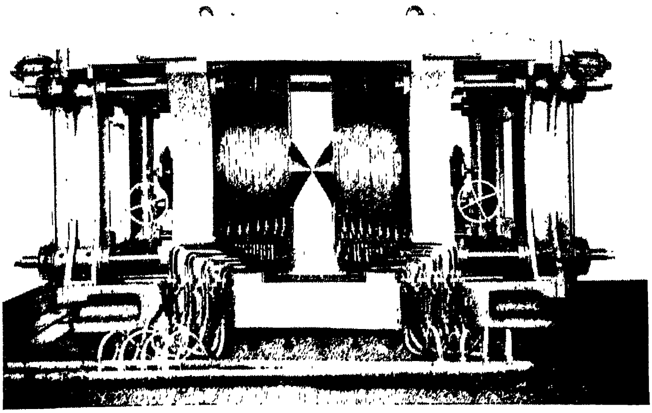
(*a*). The 70-ton permanent magnet at Bellevue used to ing the speeds of α particles. The large rings and t pieces are of soft iron; the permanent magnet blo inside the coils used for magnetizing them (p. 157).



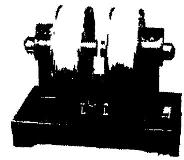
(*c*). The magnet of an electricity meter recording domestic power consumption. It is about 2 ins. long (p. 156).

(*d*). The magnet of an ammeter. The coil fits into the upper hole and is twisted when a current flows. The whole magnet is about 2½ in. across. (p. 35).

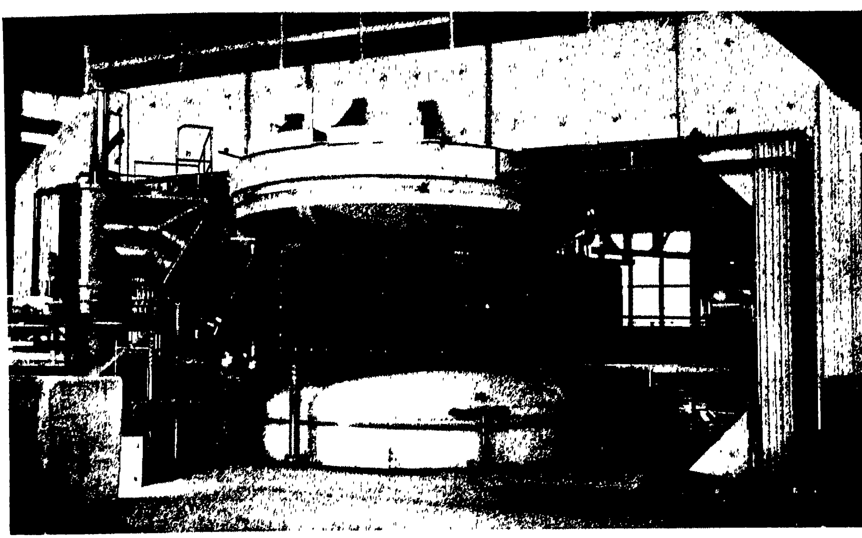
(*e*). This permanent magnet has a field 4,000 gauss in its gap, in which a magneti can be placed. The base of the magnet 10 in. long (p. 156).



(*a*). The 110-ton electromagnet at Bellevue; the cables and pipes visible in front, supply the electricity and cooling water to the magnet coils. In the gap shown a field of about 50,000 gauss can be produced. The magnet is about eight feet high (p. 162).

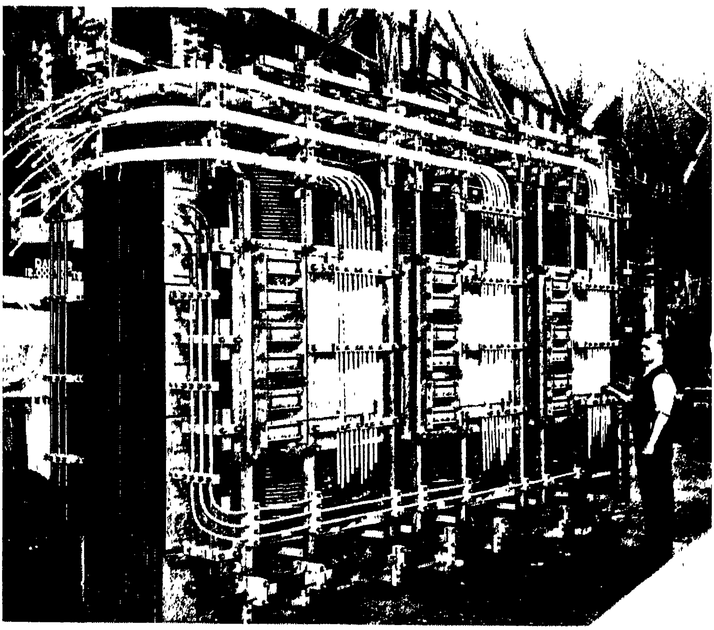


(*b*). A small electromagnet in the Cavendish Laboratory, Cambridge. The base is about 9 in. across (p. 162).

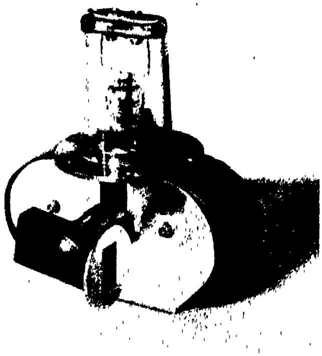


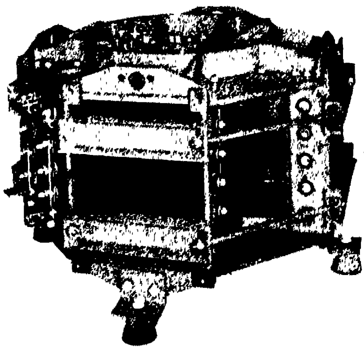
(*c*). The giant synchro-cyclotron at Berkeley, California. The magnet coils are in the conical containers above and below the central "D-box." The pole pieces (not visible) are about 15 feet across, and the whole magnet weighs about 4,000 tons (p. 163).

Right :
(*a*). The internal construction of a 60,000kW transformer used on the electric supply grid to transform down from 132,000 volts to 33,000 volts. It contains 50 tons of sheet steel and the power loss is about 120 kW (p. 124).

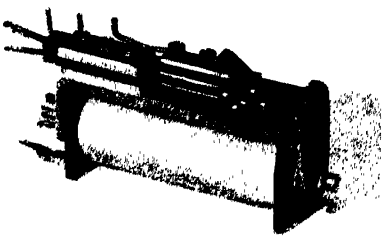


Below:
(*b*). A modern type magnetron in which the magnet (more compact than that of plate VI (*e*)) is built round the valve. The 3 cm. waves come out of the rectangular slot. The whole apparatus is 6″ high (p.176).





(*c*). A betatron for accelerating electrons to 16 million volts built by B.T.H. Ltd. at Rugby. The vacuum tube is right inside the magnetizing coils. The apparatus is about 2½ feet across (p. 175).



(*d*). A simple type of telephone relay used extensively by the G.P.O. The long tongues carry the contacts which are made and broken by the rocking of the iron piece at the right. The relay is about 4 in. long (p. 195).

product of an integer multiplied by the integer plus two (for instance, square root of 5 × 7, which is 5·9). With this modified method of calculating μ, Langevin's original formula still holds good.

The theory is too mathematical to describe in detail, but we must mention one startling new idea which it brought in and which throws a new light on the essential mechanism of magnetism. This is the idea of *electron spin*. Actually this concept was brought in not so much to explain paramagnetism as to explain some mysterious details of optical *spectra* (the kind of light emitted by hot substances). Uhlenbeck and Goudsmit found that these mysteries could be resolved if they imagined the electron to have an intrinsic *spin* (like a top) with which just one Bohr magneton of magnetic moment was associated. This spin magnetic moment was in addition to the magnetic moment the electrons produced in virtue of their orbital movement and had to be combined with the orbital moment in a complicated way. Later, Dirac was able to show by a very ingenious mathematical treatment, that if Einstein's theory of relativity were combined with Schrödinger's quantum mechanics this electron spin, with its associated magnetic moment, could be predicted.

To sum up our discussion of atomic magnetic moments, we can say that an atom may possess a magnetic moment partly due to the orbital motion of its electrons, and partly due to an intrinsic magnetic moment of each electron associated with an intrinsic spin. These various contributions partly annul each other (completely in the case of diamagnetic atoms), but in some cases partly add up together to give a net magnetic moment of a few Bohr magnetons. It will be noticed that we have assumed all along that the various magnetic moments (orbits and spins) within an atom do not act independently when a magnetic field is applied. They are in fact strongly bound

together to produce a total magnetic moment for the atom, and it is only the atom as a whole with this total magnetic moment which is acted on by a field. Both kinds of magnetic moment (orbital and spin) are associated with a rotational movement (or with angular momentum, to give it its technical name)—with the rotation in orbits in the one case and with spin in the other, and as a result an atom which has a magnetic moment always has an intrinsic angular momentum as well. A magnetic atom can in fact be imagined as a kind of magnetic spinning top magnetized along the axis of the spinning top. We shall see in the next section that this spinning top analogy is capable of very direct demonstration.

4. *Experiments to prove the reality of atomic magnets*

Imagine a gas, each of whose atoms has a magnetic moment, placed in a magnetic field. On the picture we have developed, the individual atomic magnets will point more or less equally often in all directions, on account of the thermal agitation of the atoms, except that the field makes rather more on the average point in the field direction than opposite to it. The quantum theory made a remarkable prediction about this state of affairs (a prediction we have not needed so far), namely that only quite a small number of directions are permissible.

According to the quantum theory, when a magnetic field is applied, the atomic magnets can only point directly along, directly opposite to, and in some cases at certain other definite directions to the magnetic field. To give a concrete example, let us consider a gas of potassium atoms (potassium is a metal at ordinary temperatures, but at high temperatures it vaporizes). The potassium atom has a magnetic moment due effectively to a single electron spin only (the effects of all its other electrons and their orbits

just cancel each other). To get its magnetic susceptibility we have to put μ equal to square root of 1×3 or about 1·7 Bohr magnetons in Langevin's formula, but for the present purpose it is simpler (and for reasons that cannot be easily explained here, actually more correct) to treat it as having exactly 1 Bohr magneton of magnetic moment. The prediction of quantum theory is that this single magneton can only point in two possible directions, as soon as a magnetic field is applied, either along or opposite to the magnetic field. The thermal agitation tries to keep the number along and opposite just equal, but the magnetic field tips the balance in favour of those along the field, so that the gas as a whole is slightly magnetized and behaves like a paramagnetic.

Stern and Gerlach suggested an ingenious experiment to verify this prediction of quantum theory, and successfully carried it out. They sent a beam of potassium atoms (produced by heating potassium in a completely evacuated furnace) between the poles of a magnet which produced a strongly inhomogeneous magnetic field. We have already seen that such a field produces a mechanical force on any carrier of magnetic moment and the force is towards stronger fields if the moment is along the field, and towards weaker fields if the moment is opposite to the field. If then, the potassium atoms are approximately equally divided into atoms with magnetic moments along and opposite to the field, this inhomogeneous field will sort out the sheep from the goats, the two kinds of atoms being deflected in opposite directions.

After the atoms have left the magnet they carry on in straight lines, but the original beam is now split into two beams on account of the two kinds of deflection while passing through the magnet. These two beams were detected by letting them fall on a glass plate where after sufficient time they produced

visible traces of potassium. When the experiment was actually carried out, the theoretical predictions were fully verified. Two traces were indeed obtained, and from the separation of the two traces the magnetic moment of the potassium atom could be deduced. It turned out to be just one Bohr magneton, as predicted by the theory. With other kinds of atoms more than two traces were obtained, but in every case the results fitted in completely with the idea that the atomic magnets could only point in a limited number of directions. This Stern-Gerlach experiment—one of the classical experiments of atomic physics—gives confidence in the essential truth of Langevin's assumption that paramagnetism is caused by the orientation of atomic magnets in a magnetic field.

Another classical experiment to test the foundations of the theory was suggested by Einstein and carried out by him and de Haas. Each atom of a paramagnetic substance can be imagined as a miniature magnetic spinning top, and when the substance is unmagnetized these spinning tops have their axes pointing quite at random. As soon, however, as a magnetic field is applied, the magnetic moments and with them the axes of the spinning tops get a little bit lined up (thus producing the observed magnetization). Now, there is a fundamental law in mechanics which says that angular momentum is always conserved, and since the lining up of the axes tends to add angular momentum to the substance, the substance must react by acquiring an opposite angular momentum as a whole. In less technical terms, this means that when a substance is magnetized it should tend to twist a little bit. This twisting tendency is proportional to the amount of magnetization produced, and turns out to be very small, but fortunately it is not too small to observe.

Since the greatest magnetization in a reasonable

field can be obtained with a ferromagnetic rather than a paramagnetic substance, Einstein and de Haas suspended an iron rod on a fine fibre and suddenly magnetized it along its length. They found that the iron rod twisted slightly from its original position, and by careful measurement of this effect they were able to confirm that it was approximately of the amount indicated by theory. Actually, more refined experiments later on showed that the effect was only half as big as predicted by a theory based on consideration of only orbital motion of electrons, and this discrepancy was in fact one of the pieces in the jig-saw puzzle whose solution led to the discovery of electron spin.

The modern view is that the magnetism of a ferromagnetic is nearly entirely due to electron spins, and Dirac's theory predicts that the angular momentum of spin is half as big as that of orbital motion in relation to the magnetic moment, so the experiment should indeed give just half the effect to be expected for orbital magnetism. This demonstration of the rotational motion associated with magnetism—the *gyromagnetic effect* as it is called—can be used in principle to sort out to what extent the magnetism of any paramagnetic substance is due to orbital and spin effects. We say in principle, because the effect is so minute with anything but a strongly magnetizable substance such as iron, that it is hardly measurable. Sucksmith, however, has recently so perfected the technique of the experiment that he has been able to work with paramagnetics and thus give further support to the detailed theory of paramagnetic susceptibility. It is interesting to note that some of these gyromagnetic experiments had to be carried out at night, because during the day the vibrations of the Bristol trams running through the town at some distance from the laboratory were sufficient to upset the delicate apparatus and make accurate measurement impossible. This

gives some idea of the difficult nature of this sort of work.

5. *The effects of interactions between atoms*

Up to now we have in our explanation of magnetism always worked out just the *average* effect per atom, and then simply multiplied this effect by the number of atoms in unit volume to obtain the magnetization. This procedure implies that we have ignored any possible interactions of the atomic magnets on each other, and we must now consider how far this is justified and in what circumstances the procedure needs modification.

Any possible interaction between atoms will depend on how close the atoms are together and so will be weakest if the substance is a gas. In fact, in a gas the atoms are on the average separated by distances of some thousands of times the size of the atom, so that apart from the collisions due to thermal agitation it is safe to assume that interaction effects are negligibly small. We should, therefore, expect Langevin's theory to apply best of all to a gas, and indeed all measurements on the susceptibilities of gases agree very well with the theory. We may mention that measurements on gases are very difficult to make, because the low density of a gas (in other words the relatively small number of atoms per unit volume) makes the volume susceptibility always very small. It is only of the order of 10^{-7} for paramagnetic gases and even less, about 10^{-9}, for diamagnetic gases. Strictly speaking, since we have been concerned with single atoms, the theory should apply exactly only for *monatomic* gases, in which the atoms do not combine to form molecules.

At ordinary temperatures the only monatomic gases are the inert gases, helium, neon, argon, etc., and it turns out that because of the very symmetrical way in which their electron orbits and spins are arranged,

the atoms of these gases have no resultant magnetic moment, and the gases are in consequence diamagnetic. At higher temperatures substances which are ordinarily solid or liquid become gases, and some of them are paramagnetic ; an example we have already mentioned is potassium vapour, which has just the paramagnetic susceptibility corresponding to its single uncompensated electron spin. Most ordinary gases, such as hydrogen, oxygen, nitrogen and so on, consist of molecules in which two or more atoms (two in the examples mentioned) are bound together. In such cases the detailed theory is rather more complicated than for atoms, but the general ideas of Langevin's theory still hold good. Such gases are mostly diamagnetic, but a few are paramagnetic with each molecule having a magnetic moment of a few Bohr magnetons. An interesting example of such a paramagnetic gas is oxygen (which comprises about 20 per cent. of the air we breathe), and its susceptibility is in very good agreement with the detailed theory for molecular gases.

In solids and liquids the atoms or molecules are much more closely packed together and their average separation is only a few atomic sizes. Interaction forces between the atoms or molecules are then much stronger (it is indeed these forces which keep the substance together), and in general it would be unreasonable to expect Langevin's theory to apply exactly. The theory of these effects is too complicated to explain here, but we can mention a few important consequences.

In some special cases, notably certain chemical salts, the theory still applies surprisingly well. In some of these salts part of the molecule has a magnetic moment which makes the salt behave like a paramagnetic, and the other parts of the molecule which are magnetically neutral act as a kind of diluting agent. The magnetic parts (the so-called paramagnetic *ions*)

are consequently still relatively far from each other even though the salt is a solid, and the interaction effects are fairly small; it turns out that they are particularly small if the magnetism is due entirely to electron spins rather than orbits. A further diluting effect is sometimes obtained by the arrangement of the electrons within the paramagnetic ion, if the electrons responsible for the magnetic moment of the ion are "screened" by other electrons whose magnetic effects compensate each other. In such cases the simple theory applies very closely and the interaction effects are practically negligible as if the substance were a gas. The detailed study of the susceptibilities of such salts was historically of importance in elucidating structure of atoms. The absence of interaction complications enabled the magnetic moments of the paramagnetic ions of a whole series of elements (the rare earths as they are called) to be directly deduced, and the changes of magnetic moment in going from one element to the next (in order of atomic number) revealed regularities in the structures of atoms which provided valuable confirmation of Bohr's theory. When the interactions are not quite negligible they usually have the effect of modifying Curie's law, but the general theory still roughly applies.

In many solids the interaction effects lead to the liberation of electrons from each atom, and these electrons are able to roam throughout the body of the solid. Such solids are metals, and if an electromotive force is applied to them, their free electrons are driven through the metal producing an electric current; they are in fact conductors of electricity. Their magnetic properties depend very much on the structure of the ion which is left after the free electrons contributed by each atom have left it. If the ion left behind has a resultant magnetic moment, the substance as a whole is usually paramagnetic (platinum is a

typical example), but owing to the strong interaction effects between the ions, the paramagnetism is usually not in detailed agreement with Langevin's theory, and in some cases, such as iron, this interaction completely changes the magnetic properties and ferromagnetism occurs (which will be discussed more fully in the next section).

If the ion has no resultant magnetic moment (this is the more common case), the metal is only feebly magnetic. Its magnetism is then generally made up of three parts; first, the diamagnetism of the ions, second, a diamagnetism due to the "free" electrons being twisted into curved tracks when a magnetic field is applied, and third, a paramagnetism due to the electron spins of the free electrons. At first sight it might seem that the third contribution should be large, since there are at least as many free electrons as atoms, and each electron carries a spin moment of one Bohr magneton, but actually the paramagnetism turns out to be very small. Fermi and Dirac showed that electrons in metals obey special laws which allow much fewer of the spins to be oriented by a magnetic field than would seem to be indicated by considering the thermal agitation effects in the ordinary way. As a matter of fact, the puzzlingly small paramagnetism of the spins of free electrons in metals was one of the clues which led to the much better understanding of metals which has been achieved in the last twenty years.

The relative sizes of the three sorts of magnetism in a metal depends very much on the particular metal concerned, since all three are usually of much the same order of magnitude. Sometimes the diamagnetism outweighs the paramagnetism and the metal as a whole is diamagnetic, as for instance lead or zinc, and sometimes the paramagnetism is predominant and the metal is paramagnetic on the whole, as for instance,

tin or aluminium. In all such cases the magnetism is very feeble, the volume susceptibility being usually less than 10^{-6}, and hardly varying with temperature. The detailed behaviour depends very much on circumstances, and interaction effects may sometimes produce curious results, as in the case of bismuth, to which we shall return later.

Solids and liquids which do not conduct electricity (insulators) are usually feebly diamagnetic (except, of course, where the molecules are magnetic, as in paramagnetic salts). There are no free electrons to complicate the issue, and interaction effects are usually not very important. We have already mentioned sulphur, as a typical example of this class of substance (p. 84).

6. *Ferromagnetism*

We have left ferromagnetics almost to the last, in spite of their technical importance, because they are really a rather special case of interaction effects, and can only be understood now that we have a general picture of what happens when interactions are relatively unimportant. Weiss in 1907 was the first to produce an explanation of the extraordinary properties of ferromagnetics. Without bothering about the detailed structure of the atoms of a ferromagnetic (indeed little was known at that time about atomic structure) he worked out the consequences of assuming a particular kind of interaction between magnetic carriers.

He supposed that owing to this interaction, the field acting on a single atom of iron (more correctly on the ion left after the free electrons had left the atom) was not merely the magnetic field applied from outside, but also a field due to the interaction, a *molecular field* as he called it, proportional to the magnetization of the whole substance. In other words, he assumed that the effective magnetic field in Langevin's theory

was not just H, but $H + \lambda I$ where λ is some suitable constant. It turned out that if λ was big enough, ferromagnetism could be explained. Why λ should have to be so big (about 100,000) was left a mystery for twenty years, until Heisenberg found a rough sort of explanation using quantum mechanics (too difficult to reproduce here), but if the large value of λ is accepted it is not difficult to see what happens.

Let us put $H + \lambda I$ instead of H into Langevin's formula for paramagnetism (we need not worry about the diamagnetism, since it is negligibly small in comparison). We get (see p. 81)

$$I = \frac{n\mu^2}{3kT} \times (H + \lambda I)$$

Solving this equation for I, we find

$$I = \frac{n\mu^2 H}{3k(T - n\mu^2\lambda/3k)}$$

As long as T is higher than $T_c = n\mu^2\lambda/3k$, this gives just a strong paramagnetism, though one which obeys a modified Curie's law (in fact the Curie-Weiss law of p. 60), but when the temperature T is just equal to T_c, the formula predicts an infinite magnetization. This is because Langevin's formula, as we have quoted it, is only a first approximation—quite good enough for ordinary paramagnetics but failing us here where we have to deal with much stronger magnetizations. This first approximation ignores the *saturation* which must set in for sufficiently high fields, even with paramagnetics, when the field is so strong that it makes all the atomic magnets line up completely. Below the critical temperature T_c, the extra molecular field is sufficiently strong to magnetize the whole substance without the help of any applied magnetic field, and we get a spontaneous magnetization.

The detailed working out of this idea shows that this spontaneous magnetization sets in only below the

critical temperature T_c and becomes larger as the temperature is lowered in a fashion very similar to that shown in fig. 32 of Chapter 3. The critical temperature $T_c = n\mu^2\lambda/3k$ has in fact just the significance of the Curie temperature, above which ferromagnetism disappears ; it is by comparing it with the experimentally found value that a value of λ of about 100,000 is found necessary. At low temperatures the spontaneous magnetization corresponds to almost perfect alignment of the atomic magnets, and so we can estimate from the experimental value of the saturation magnetization, the magnetic moment of a single atom. For iron the biggest magnetization is about 1,700 per unit volume, which contains roughly 10^{23} atoms, so each atom has a moment of nearly 2×10^{-20} or about 2 Bohr magnetons. This is just the order of magnitude we should expect for an atomic moment.

According to Weiss, then, the interaction effects between the atomic magnets in a ferromagnetic are so strong that it can magnetize itself, provided the temperature is not too high. As the temperature is raised, the increasing thermal agitation reduces the size of this spontaneous magnetization, and moreover it reduces it more and more rapidly because the molecular field which produces the spontaneous magnetization becomes weaker and weaker. As we approach the Curie temperature, the spontaneous magnetization falls off very rapidly and above this temperature the thermal agitation is too strong to permit any spontaneous magnetization at all, and the ferromagnetic turns into a paramagnetic.

It would seem on this view that, below the Curie temperature, every ferromagnetic should be just a permanent magnet, while we have seen that usually a ferromagnetic is only weakly magnetized without a field, and only with the help of a small external field

is strong magnetization produced. The reason for this apparent discrepancy with the facts was also given by Weiss. He suggested that in the absence of an applied field, the spontaneous magnetization had different directions in different regions or *domains* of the ferromagnetic substance. He supposed that each domain was large enough to contain very many atoms, but that it was still fairly small compared with ordinary sizes, and so could not be easily detected. Since the magnetic moments of the domains point in various directions the substance as a whole need not have any spontaneous magnetization, because the effects of the various domains just annul each other (in a permanent magnet they only partially cancel out, and we do in fact get a certain degree of spontaneous magnetization). When a quite small magnetic field is applied, the magnetic moments of the domains are lined up and we get saturation when they all point the same way.

Weiss showed remarkable intuition in putting forward this domain idea, because at the time there was no direct evidence for it, apart from the indirect evidence that a ferromagnetic was not always a permanent magnet. More recently, however, a great deal of direct evidence has been found, and we shall devote the whole of the next chapter to the domain theory, showing how it explains the detailed properties of ferromagnetics such as high permeability and hysteresis, which are so important technically.

The general idea of Weiss' theory that a ferromagnetic consists of spontaneously magnetized domains has survived to the present day, but the details have been a good deal modified by the quantum theory. Even now a lot remains to be explained, because, actually, the interaction effects are more complicated than Weiss supposed, and the mathematical problem of working out their influence is so difficult that only simple limiting cases have been solved. One important

result which has come out of all this work is that the magnetism of a ferromagnetic is almost entirely due to electron spins, rather than orbital motion of electrons (this is shown for instance by the gyromagnetic experiments described on p. 91). In a sense, the wheel has turned full circle: in Chapter 2 we suggested that the ultimate magnetic entity was not a magnet at all but electricity in motion, while now we see that though electricity in motion (orbital motion of electrons) is required to explain a good deal about magnetism, we still need a fundamental magnet (the electron spin moment) to explain the magnetism of an ordinary permanent magnet, and we return to the primitive idea of magnetism *per se*, as it were. In a deeper sense, however, this attempt to decide whether electricity or magnetism is the fundamental entity is rather like the problem of whether the chicken or the egg came first, for in Dirac's theory the magnetic properties of electron spin appear as a fundamental consequence of relativistic quantum mechanics, and it becomes rather artificial to separate electricity and magnetism at all.

7. *Some magnetic curiosities*

Our aim so far in this chapter has been to give a general picture of how magnetic properties of different kinds of materials can be explained. In certain extreme cases, rather remarkable magnetic properties occur because of special circumstances, and we shall conclude this chapter with an account of three such cases which, though not of much practical importance (except to the academic scientist as a testing ground for his theories), are worth describing as magnetic curiosities.

The first example is the *ideal paramagnetic*. We have mentioned that, in certain favourable circumstances, interaction effects may be almost com-

pletely absent in a paramagnetic salt. This means that the simple theory, and in particular Curie's law, applies very closely down to very low temperatures. At ordinary temperatures, the susceptibility of such a salt, for instance, potassium chrome alum is about 2×10^{-5}, and so at 1 °K it becomes 300 times

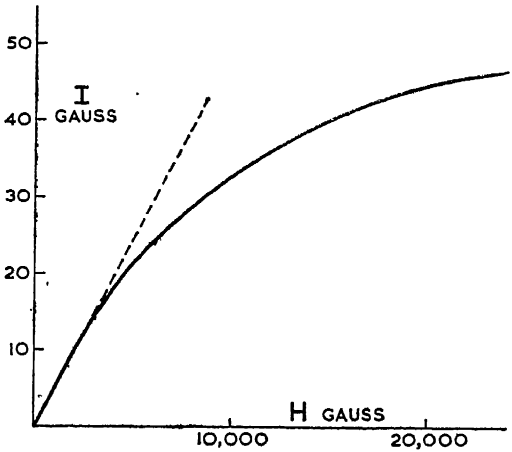


Fig. 36.—Magnetization curve of potassium chrome alum at 1·34°K. (this temperature is achieved by boiling liquid helium at reduced pressure). The initial volume susceptibility (measured by the slope of the straight line) is 5×10^{-3}, but for fields above a few thousand gauss, the curve departs from the straight line, and a saturation magnetization of about 60 gauss is approached at higher fields.

as big or 0·007, and we have a fairly strong magnetism in quite modest magnetic fields. For instance, in a field as low as 1,000 gauss, we should have a magnetization of 7—which is only 250 times less than the

saturation magnetization of iron. Actually, at such low temperatures the thermal agitation is so small that saturation effects can be observed if the field is increased above a few thousand gauss.

As the field is increased, its orienting effect is able to gain control over the disordering forces of the thermal agitation and the atomic magnets get almost completely lined up in a field of 20,000 gauss. The magnetization stops increasing proportionally to the field and at high enough fields stops increasing any further (this behaviour is illustrated in fig. 36). The saturation magnetization is almost comparable to that of iron,* and so we have the remarkable case of really strong magnetism in a substance which we should ordinarily think of as only feebly magnetic. In principle this saturation should be observable by using a high enough magnetic field even at ordinary temperatures (say 300 °K) but the field required would be 300 times as big as that required at 1 °K. This means a field of several million gauss, so the experiment is impracticable with the means at our disposal. Kapitza looked for saturation with a field of 300,000 gauss, the highest field yet obtained, but could find no trace at ordinary temperatures, just as we should expect.

At still lower temperatures, obtainable by a special technique we shall describe in Chapter 7, the properties of these ideal paramagnetics become even more striking, and recently Kürti and Simon found that at about 0·01 °K iron ammonium alum behaves somewhat like a ferromagnetic, showing hysteresis and a Curie point. Further investigation of these properties may yet throw light on some of the difficult

* The fact that the saturation is some 30 times smaller than in iron is due to the much smaller density of magnetic carriers. The moment of each carrier (a chromium ion) is 3 Bohr magnetons, which is greater than for iron (which has 2·2 Bohr magnetons per atom) but there are about 40 times less chromium ions per cc. than there are iron atoms in a cc. of iron.

features of ferromagnetic theory, and if this proves to be the case it will be an interesting example of how academic science can be of practical value even when it studies effects in completely extreme conditions, which themselves are unlikely ever to be of practical use.

Our second example is bismuth, a diamagnetic metal. From the point of view of the theory of metals it has always been somewhat of a "rogue" metal and the elucidation of its properties has been useful in stimulating a deeper understanding of the theory. Bismuth is more diamagnetic than it should be according to a naïve theory. Its volume susceptibility is about 10^{-5}, which is some twenty times larger than simple theory predicts and, moreover, it increases fairly strongly as the temperature is reduced. That this is due to some sort of interaction effects is clear from the fact that when it melts (and the interaction effects due to the regular arrangement of its atoms in a solid disappear) the diamagnetism drops suddenly to a reasonable value.

We cannot explain here how these interactions between the free electrons and the atomic lattice structure influence the magnetic behaviour, but it is worth describing a very peculiar effect which is caused by these interactions and which sets in with bismuth at low temperatures. It was found by de Haas and van Alphen that below about 20°K. (the temperature at which liquid hydrogen boils) the magnetization of bismuth is no longer proportional to the magnetic field and the susceptibility varies with field in the peculiar fashion shown in fig. 37. The effect is only observed in very pure single crystals of bismuth and gets stronger as the temperature is lowered. The theoretical explanation of this behaviour was given by Peierls and Landau, and it turns out that it can only occur with very special circumstances of inter-

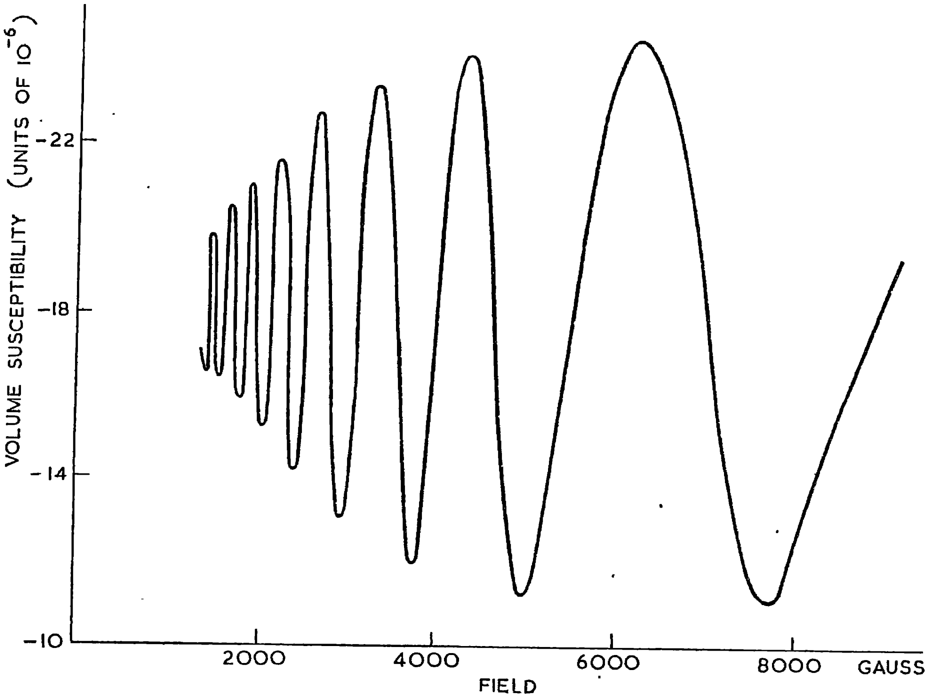


Fig. 37.—The variation of the susceptibility of a single crystal of bismuth with the magnetic field perpendicular *to the "trigonal" axis of the* crystal, at the normal boiling point of liquid helium (4·2°K.).

action, so in a sense it is rather a fluke that it occurs at all, and the effect has been found with only one other metal—zinc.*

Superconductors provide our last example of magnetic curiosities. Certain metals, such as lead, tin, or mercury, at very low temperatures (usually below 10 °K) become *superconducting*, that is to say they lose all their electrical resistance and can pass an electrical current without any electromotive force to drive it. This leads to very remarkable magnetic properties. If a magnetic field is applied to a metal, Faraday's law of induction predicts that circulating currents will be induced, so-called *eddy currents*, which try to build up a counter field and keep the *status quo* as it were. Normally these eddy currents just die away, owing to the electrical resistance of the metal, which dissipates their energy as heat. If, however, there is no resistance at all, the currents continue to flow. In this case, we can think of the metal as having zero magnetic permeability, for the currents induced have a strength which is just sufficient to neutralize the magnetic field which is being applied (these currents actually flow only on the surface of a superconductor). In terms of susceptibility this means a very strong diamagnetic susceptibility: the induced currents keep B just zero, so we have $H+4\pi I=0$, or $I=-H/4\pi$. In other words, the diamagnetic susceptibility is $1/4\pi$ or about $\frac{1}{12}$. This is much greater than any other known diamagnetic susceptibility—10,000 times greater than that of bismuth, for instance, which is the most diamagnetic of ordinary substances.

The property of superconductivity is destroyed if too large a magnetic field is applied, and since the *critical field* is rarely more than a few hundred

* Since this was written, however, the effect has been found in two more metals, gallium and tin, so perhaps it occurs more generally than suggested in the text.

gauss, the greatest diamagnetic magnetization that can be obtained is not much more than 50 or so; for higher fields the currents responsible for the diamagnetism die away, and only the usual feeble dia- or paramagnetism of the metal is left.

It used to be thought that this extraordinary magnetic behaviour was just a consequence of the vanishing of electrical resistance, but more recent experiments have suggested that the high diamagnetism is an independent property. For instance, if a metal is made superconducting by cooling it in the presence of a magnetic field, it is found that the lines of force are pushed out of the metal (or in other words B becomes zero) at the same moment as it loses its electrical resistance, although in these circumstances the zero permeability cannot be explained by Faraday's law of induction (since only the temperature has been changed). To the scientist, one of the most interesting aspects of superconductivity is that no one has yet found any real explanation of it, and so it provides a real "Tom Tiddler's Ground" for exciting new experiments, rather than a subject in which the research worker can only hope to dot the i's and cross the t's of what is already known.

Chapter Five

MORE ABOUT FERROMAGNETISM

1. *Direct evidence for spontaneously magnetized domains*

ACCORDING to Weiss's interaction theory of ferromagnetism, a piece of iron, or any other ferromagnetic, is made up of small regions, each of which is spontaneously magnetized to saturation. If these domains have their directions of magnetization pointing more or less at random, the substance as a whole is unmagnetized, and a small magnetic field is required to produce a "bulk" magnetization; if, however, there is any tendency for the domains to point in any particular direction, the substance will be magnetized even without any applied field, and we have a permanent magnet. In this chapter we shall describe some of the evidence which shows that these domains really exist and then discuss what factors decide the arrangements of the domains. These are the factors which determine the shape of the whole magnetization curve of the ferromagnetic and so decide for what kind of technical uses it is most suited.

If the magnetization curve of a ferromagnetic is highly magnified, it is found to be not quite smooth, but made up of many irregular jumps (fig. 38). This was first discovered by the German, Barkhausen, in an ingenious but indirect manner. He wound a coil round an iron rod, and connected the coil through an "amplifier" to a pair of telephones. When the iron was magnetized by a gradually increasing field, a peculiar irregular rustling noise was heard in the tele-

phones, the noise being loudest at the steepest part of the magnetization curve. A more detailed analysis of this Barkhausen noise showed it to be due to the irregular form of the magnetization curve illustrated in fig. 38; at each little jump of the magnetization curve, an impulsive current is induced in the coil round the iron rod, and the rapid succession of these impulsive currents produces the observed noise in the telephones. This was proved by Bozorth (working in the American Bell Telephone Laboratories), who used an arrangement rather like Barkhausen's but connected a measuring device—a cathode ray oscillograph—to the coil instead of telephones. In this way he was able to estimate the size of the jumps shown in fig. 38.

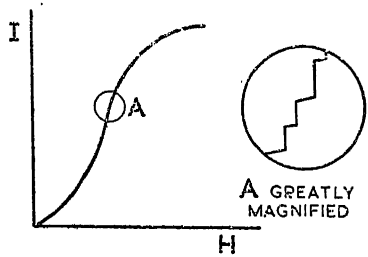


Fig. 38.—If the magnetization curve of a ferromagnetic is greatly magnified, it is found to consist of a series of small jumps, which correspond to sudden changes of domain magnetization.

The Barkhausen effect finds a very simple interpretation in terms of the domain idea, and so provides very direct evidence for its truth. As the magnetic field is increased, a domain, whose magnetization is not pointing in the field direction, suddenly swings its magnetization direction into the field, and so produces a small jump in magnetization. Each domain requires

a certain critical magnetic field to swing it round, rather as a compass needle restrained by a very weak thread would require a certain critical field to snap the thread and jump round into the field direction. From the size of the jumps, Bozorth was able to estimate the size of the domains, assuming each domain to be magnetized to the known saturation intensity of the material. He found that the domain sizes were very variable, but their average size was about 10^{-4} cm. in the particular material he studied, and the biggest domains turned round while the steepest part of the magnetization curve was being followed.

Another line of direct evidence for the reality of domains was discovered by Bitter at the Massachussets Institute of Technology. He had the ingenious idea of sprinkling very fine iron filings over the surface of a polished piece of ferromagnetic, and when he examined the surface with a microscope, he found that the filings were arranged in complicated but regular patterns. These *Bitter patterns* depend very much on the state of the surface and the kind of material used, and they are best seen if a highly polished single crystal of the metal is used. Elmore, a colleague of Bitter's, developed and perfected the experimental technique and obtained beautiful patterns of which typical examples are shown in plate I. The domains can be thought of as small permanent magnets, and the iron filings tend to settle where two of them come together, so that the pattern really reveals the arrangement of the domains near the surface of the iron crystal. To prove that this is the true interpretation of the patterns, Elmore built up a model of little permanent magnet cubes placed side by side, and by sprinkling the surface of these cubes with iron filings, he was able to produce a pattern very similar to the maze patterns actually observed (see plate I*b*). Many other ingenious experiments have been made by Bitter, Elmore and

others to elucidate the arrangement of the domains in a ferromagnetic by this method. Although the real existence of domains has been placed beyond any reasonable doubt, there is still a lot to be cleared up, for the method can only give information about the state of affairs at the metal surface, and this may be very different from the interior of the material, and moreover depends very much on how the surface has been prepared.*

The third line of evidence on domain structure is less direct than the Barkhausen noise and the Bitter patterns—it is the success of the idea in explaining many of the detailed features of the magnetization curves of actual ferromagnetic materials. By a curious coincidence this line of evidence is also associated with a name beginning with B, for it has been the German, Becker, who has been most responsible for developing the theory of how the domain structure influences the all important technical properties of a ferromagnetic, which are summarized in its magnetization curve. We shall now give an account of the basic ideas behind Becker's work.

2. *What decides the magnetization direction of a domain?*

There are three main factors which cause a ferromagnetic to break up into domains, and which decide the arrangement of these domains. These factors are the shape of the substance, its crystal structure, and its internal mechanical stresses; we shall discuss these in turn.

If the whole of a piece of ferromagnetic material were to be spontaneously magnetized with a single

* Since this was written, Williams and Bozorth have shown that the particular form of the patterns found by Elmore is due to the mechanical strains set up by polishing. If polishing is done by the electrolytic method, which produces no strains, a quite different pattern is obtained (illustrated in plate I*d*).

direction of magnetization, the demagnetization effect explained in Chapter 3 would come into play, and the field of the poles developed on the surface of the piece would try to demagnetize it. In other words, spontaneous magnetization of the whole piece would not represent a stable state of affairs, and the material must break up into domains in such a way as to minimize the demagnetization effect. The theory of how this breaking up takes place is very complicated and depends also on the other two factors which we have not yet considered. We cannot go any deeper into the question of how shape affects the domain arrangement, but it is important to remember that this shape effect is basic, and that domains would still occur even if the other domain causing factors did not exist. For our purposes we can ignore shape effects by always thinking of a shape in which demagnetizing effects are negligible—either a very long thin rod or a closed ring. In such cases the other two factors are dominant, and it is permissible to forget about the shape effect.

All solid matter is made up of crystals, and within each crystal the atoms are arranged in a regular lattice. In iron and nickel this regular arrangement is a cubic one. We can imagine a large number of cubic boxes piled together in a regular way, and we get a picture of the lattice by supposing atoms to be placed at each cube corner, and also at the centre of each cube (in the case of iron), or at the centre of each cube face (in the case of nickel). These arrangements are illustrated in fig. 39. Any ordinary piece of iron or nickel is made up of a large number of such crystals put together, the cube edge directions of the various separate crystals pointing in arbitrary directions. The size of the single crystal *grains* within which the regular arrangement is preserved depends very much on how the material has been prepared; by suitable

treatment the grains can be made very large, and it is possible even to make a whole piece of material into a single crystal grain, all having the same orientation. To get at the basic mechanism of any process, it is always simplest to consider what will happen in a single crystal, since the processes in an ordinary material made up of many crystals (a so-called *polycrystalline* material) will always represent an average over the properties of its constituent single crystals.

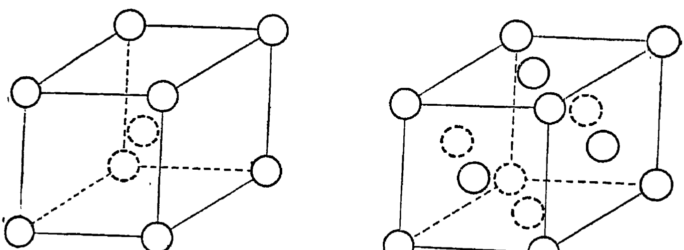


Fig. 39.—The arrangement of the atoms in body centred and face centred cubic lattices. In each case only one so-called "unit cell" is illustrated; to picture the whole lattice the unit cell must be imagined repeated indefinitely in all directions.

Very illuminating experiments were made on the magnetic properties of single crystals of iron by Honda and Kaya in Japan and by Webster in Cambridge, about 20 years ago. They found that a single crystal of iron was more easily magnetized along a cube edge (a [100] direction as it is called) than in any other direction. This is illustrated by fig. 40, which shows the magnetization curves obtained with the magnetizing field in three typical

directions: the cube edge direction, [100], the diagonal of a face, [110], and the diagonal of the cube, [111]. Somewhat similar curves are obtained with nickel, except that the *easy direction* is the cube diagonal, [111], direction instead of the cube edge. The natural explanation of these results is that the interaction forces which hold the atoms together in a regular lattice, make it more easy for the spontaneous magnetization to lie in a particular crystal direction (the cube edge in iron, the cube diagonal in nickel) than in any other.

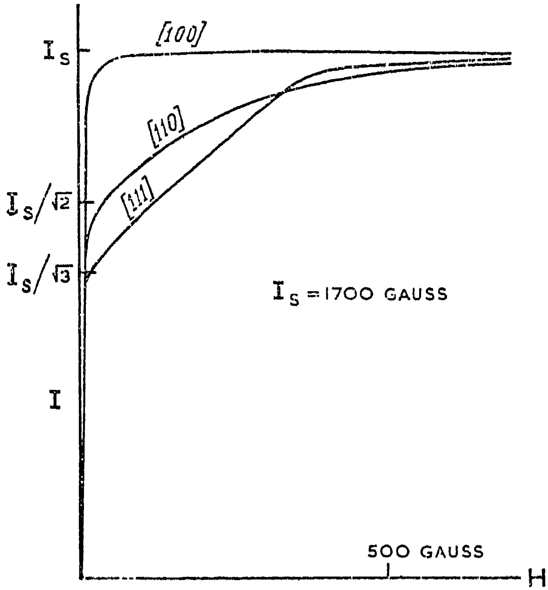


Fig. 40.—Magnetization curves along three directions in a single crystal of iron. The [100] direction is along a cube edge, the [110] along a face diagonal, and the [111] along a body diagonal.

Let us consider the case of iron in a little more detail. If we assume, as is suggested by the experimental results, that the easy direction is a cube edge, then in the unmagnetized state of a single crystal the spontaneously magnetized domains will all be magnetized along cube edge directions. There are, of course, six such cube edge directions (since the magnetization can point either way along each of the three cube edges), and in the unmagnetized state the crystal will be split into a large number of domains, with approximately equal numbers magnetized in each of the six easy directions, producing no net magnetization in any one direction. A sketch illustrating this arrangement schematically (but showing only four of the six possible directions) is shown in fig. 41*a*. Now suppose we apply a small magnetic field to the crystal. If the field is parallel to a cube edge, all the domains

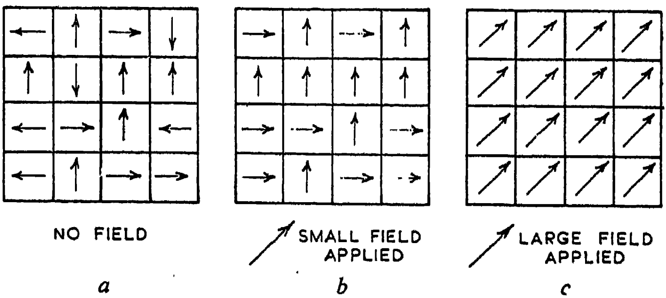


Fig. 41.—Schematic illustration of the processes when a single crystal of iron is magnetized along a face diagonal [110]. The arrows indicate the directions of magnetization of the domains. In practice the domain boundaries would be more complicated ; for simplicity the third possible direction of magnetization (into and out of the paper) has been omitted.

will at once swing into this direction, and the crystal will be magnetized to saturation in very small fields, as is in fact found to happen.

If the field is applied parallel to a face diagonal [110], however, the first thing that will happen is that the domain directions will swing into one of the two cube edges nearest to this face diagonal (fig. 41*b*) and will produce a net magnetization of $1/\sqrt{2}$ or 0·7 of the saturation intensity (since the domain directions are then at 45° to the field direction). For further increase of field, the magnetization can only increase by the domain directions twisting out of the easy cube edge direction and if we suppose this requires expenditure of work, we can understand why the magnetization only increases gradually with field above 0·7 of saturation. A theory of this twisting process has been worked out, and it correctly explains the shape of the magnetization curve and shows that a certain field is necessary to complete the twisting process. When this field (about 500 gauss) is reached, all the domains lie along the field, having been twisted by 45° from the " easy " cube edge direction, and we again have saturation (fig. 41*c*).

A similar argument explains what happens if the field is applied along the cube diagonal [111] direction. This direction is at 54° to a cube edge, and so the magnetization rises abruptly to $1/\sqrt{3}$ (this is cos 54°), or about 0·58 of saturation, for a very small field, when the domains all take up one of the three cube edge directions pointing in the same sense as the field. Further increase of magnetization again requires twisting out of these " easy " directions, and so is more gradual.

From these considerations, we see that a single crystal of iron is an " ideal " ferromagnetic along any cube edge direction, for it is magnetized to saturation in very small fields. In other directions the single

crystal behaves "ideally" only up to magnetizations of 0·58 or more of the saturation and then is less easily magnetizable. In a polycrystal (an ordinary piece of iron), the cube edge will have a different direction relation to the field in each grain, and we should get some sort of average curve, still rising very steeply up to about 0·58 of saturation, but requiring a field of a few hundred gauss to achieve saturation. So far, however, the theory gives no clue as to what determines the steepness of the steep part of the magnetization curve, or, for that matter, what decides the particular cube edge direction of any particular domain in the unmagnetized state.

According to the theory as we have explained it up to now, the steep part should in fact be just vertical, for the smallest field should be sufficient to cause the swinging of domains into the easy direction pointing most nearly along the field. To understand what prevents the curve from being completely vertical in its initial part, we have to consider the factor of internal mechanical stresses which we have so far ignored. No substance is completely free from internal stresses, and in fact we have over-idealized our picture by describing a single crystal as a completely regular lattice of atoms. In reality, there are always irregularities either due to foreign atoms of impurities causing dislocations of the regular arrangement, or because of slight mechanical stresses which break up the regularity and make the distances between atoms slightly less in some places and slightly more in others. We can roughly think of these stresses as squeezing up the lattice slightly in some places and stretching it in others.

Now if the lattice is stretched locally, it turns out that the six easy directions are not quite equally easy. For iron the two cube edge directions along the stretching become slightly easier than the others, and so the domain magnetization is along either of these two

directions. We can see now that if the stretching direction varies at random all through the crystal (as it usually does) so too will the domain magnetization direction. The domains will still have their magnetization directions in one of the six cube edges, but at any particular place only two of the directions will be stable according to the direction of the local stress. When this stress direction changes sufficiently we go over from one domain to another.

The effect of stress in deciding the easiest directions of magnetization is closely tied up with an effect called *magnetostriction*. When a ferromagnetic is magnetized it slightly changes its length (by only a few parts in a million, usually), and this magnetostrictive change of length is all important in deciding the influence of a stress. If, for instance, as in iron magnetized along a cube edge, the length increases, stretching along a cube edge makes this the easiest direction. If, however, as in nickel, the length decreases, the easiest direction is at right angles to the stretching.

The effect of the internal stresses depends very much on how big they are. If they are very small, they merely decide which of the easy directions in the crystal are the easiest of all, and the steep part of the magnetization curve is no longer quite vertical, because a certain field is necessary to overcome the preference of the domains for their stress determined easiest directions. Becker has shown that the initial steepness of the magnetization curve can be estimated if the stresses and magnetostriction are known. It turns out that the very initial part of the curve corresponds to what Becker calls "90° domain changes." In this part of the magnetization curve, the domains pointing nearest the field direction grow at the expense of domains with their magnetization at right angles, and the slope of the curve (the initial susceptibility) is

proportional to the square of the saturation magnetization and inversely proportional to the magnetostriction and the average internal stress. For further increase of field (still on the steep part of the curve), we get "180° domain changes" in which the domains with magnetization pointing along the field grow at the expense of those with magnetization at 180° (opposite to the field). It should be noticed that these two kinds of domains are equally favoured as far as stresses are concerned, and we have not yet explained why the 180° changes do not happen at once: we shall return to this question a little later. The 180° changes are the ones which cause most of the Barkhausen noise and once they are complete, the magnetization curve gets much less steep and the twisting of domain directions sets in to complete the orientation process.

If the stresses are big enough, the whole picture is rather modified, for then the stress effects may completely predominate over the crystal effects. For a very strong stress, the domain direction becomes entirely determined by the direction of the local stress, even though this direction is no longer what would have been an easy direction in the unstressed crystal. In this case there are no longer just six easy directions, but the domains depend only on the stress directions, and can point in any direction whatever. The magnetization process is now somewhat different. If the applied field is small enough it starts twisting the domain directions out of their stress determined directions more nearly into the field direction, and this again (in spite of the different process) leads to an initial susceptibility proportional to the square of the saturation magnetization and inversely proportional to the magnetostriction and the average internal stress. This susceptibility is, however, much smaller than previously, since we are supposing the stresses to be much bigger. As the field is further increased, it

initiates the 180° changes, when it is sufficiently large to make a domain pointing opposite to the field switch round (just as before, the local stress decides only the *line* of the domain direction, but not which way the magnetization shall point along the line); this is the steep part of the curve. In the case of a single crystal with small stresses the domain "jumps" became complete for a fairly definite magnetization and only then did twisting start, but here the twisting and jumping are inextricably mixed and, in fact, twisting of domain directions is the main process both before and after the steep part of the curve.

When the stresses are neither too strong nor too weak, the magnetization process is a complicated combination of the crystalline and stress effects, neither being predominant. In this case it is hardly possible to give any complete description, for the various effects already described are very much confused and take place simultaneously. The domain directions are partly decided by the crystal forces and partly by the stresses and no useful general theory can be given.

3. *The explanation of hysteresis*

The explanation of hysteresis is very closely tied up with the "180° domain changes" which are involved in the steep part of the magnetization curve. We have already explained that in the absence of a field a domain is equally stable with its magnetization pointing either way along any particular line: the stress can determine only the direction of the line but not the sense of the direction along the line. When a field is applied, only the direction in the same sense as the field remains stable (as with a compass needle), and it would seem at first sight that the domain magnetization direction should then always switch round if it was opposite to the field. In fact, however, this cannot happen until the field is big enough.

The domain magnetization direction cannot actually turn, for in turning it would have to pass through directions which were energetically not possible. The only way it can change from " opposite " to " along " is by a boundary between the two kinds of domains moving along, so that the " along " domain grows at the expense of the " opposite " one which is at 180°. Now such a domain boundary between " along " and " opposite " domains has a certain energy associated with it and if there is any irregularity of stress the boundary requires a certain field to move it. A rough analogy is a buckled tin can bottom, which requires a certain force to buckle it from one stable position to the other; once this force is exceeded the can buckles over and no movement is caused by any further increase of force.

This analogy gives the clue to the cause of hysteresis. Most of the 180° changes are irreversible; once the field required to initiate these changes is exceeded, the change goes forward of its own accord, but when we reduce the field again the change does not go backwards until the field has a sufficient opposite value. This is very similar to our tin can bottom which, once buckled over, stays buckled even if the buckling force has been removed, and an opposite force has to be applied before it will buckle back to its original position. We now get a rough picture of remanence and coercive force. Consider the case of " strong " stresses, where the domains directions are entirely decided by the stresses. If after the substance has been saturated (all the domain magnetizations twisted into the field), the field is again reduced to zero, the directions will twist back again to the original state except that all the " opposite " domains have become " along " domains irreversibly during the magnetization process, and do not return to their opposite directions.

This is illustrated by fig. 42, which shows schemati-

cally the state of affairs originally and after the field has been applied and removed. A simple calculation shows that if the original domain directions are distributed quite randomly, the remanence due to the

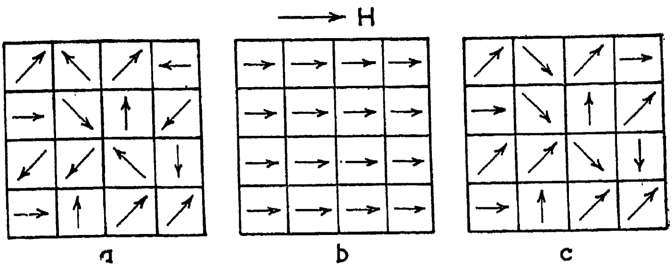


Fig. 42.—Schematic illustration of how remanence comes about when the domain directions are decided by local stresses. The original unmagnetized state is shown in (*a*). When a strong field *H* is applied, all the directions line up with the field as in (*b*) and saturation is obtained. When the field is removed (*c*) the magnetizations of the domains point along the same directions as in (*a*) but now all have the sense imposed on them by the field, and the material has a remanence of about half the saturation magnetization.

absence of "opposite" domains is just half the saturation magnetization. This is indeed the usual sort of remanence obtained, but it is often appreciably different from half because of special circumstances which cause "preferred" directions for the domains (usually due to the stresses not being random). For instance, if only *two* domain directions are possible, "along" and "opposite" some particular line, the remanence will be 100 per cent. of the saturation magnetization, all

the "along" directions being lined up completely when the saturating field is removed (see fig. 43).

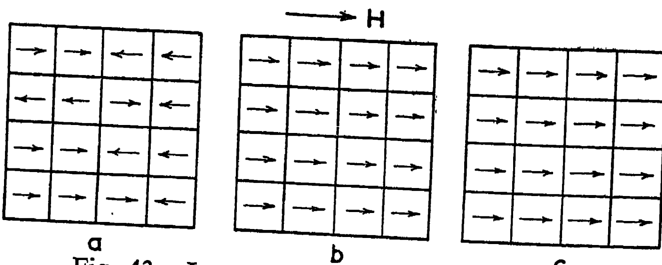


Fig. 43.—In some special materials, the domains can be magnetized only in a certain direction (the horizontal .direction in the diagram). In the unmagnetized state (*a*) as many domains are magnetized to the left as to the right. When a strong field *H* is applied to the right the domains all become magnetized to the right and the material is saturated (*b*). When the field is removed nothing further can happen (*c*) and the remanence is 100 per cent. of saturation; only if a field to the left is applied can the magnetization be changed at this stage.

If now the field is applied in the reverse direction it will have to attain a certain value before it is able to create "opposite" domains and make them grow at the expense of the "along" domains, so that it can kill the remanence. The mechanism of this coercive force, the field necessary to reduce the magnetization to zero, is a very complicated matter and has not yet been fully understood. It is clear, however, that the size of the coercive force depends on the irregularity of the internal stresses, and the values of observed coercive forces can be qualitatively explained by the theory even in its present incomplete state.

4. *Special magnetic materials for special purposes*

We shall see in Chapter 8 that the industrial and technical applications of magnetism nearly always involve the use of ferromagnetic materials, and in every case it is very important to use the right kind of material for the particular application concerned. Broadly speaking, there are two kinds of applications, the one requiring magnetically soft materials with a very high permeability and as little hysteresis as possible, and the other requiring magnetically hard materials with a very high remanence and very high coercive force, or in other words as much hysteresis as possible. To meet these opposite requirements a great variety of special materials has been developed and the theory of domain structure, which is basic in explaining how the properties depend on the method of preparation, has been a useful guide in this development.

One of the biggest uses of soft ferromagnetic material is for the cores of coils either in *electrical transformers* or in electrical machinery (such as dynamos and motors). We shall give a short account of the transformer problem, since the requirements of the ferromagnetic material in a transformer core are very similar to those for the other applications. A transformer is an arrangement of two coils wound close to each other, so that if there is a changing current in one coil (the *primary* coil) a changing E.M.F. is induced in the other (the *secondary* coil). If the primary coil has few turns and the secondary many turns, a low alternating E.M.F. applied to the primary will produce a high alternating E.M.F. in the secondary, and we have a "transformation" of the voltage. The efficiency of the transformation is much improved by introducing a common core of a high permeability material such as iron into the two coils, and it is the choice of the best material for such a core with which we are concerned. Such transformers have a great many uses, both in

what is called "heavy current" engineering and also in "light current" engineering.

Transformers play an essential part in the "heavy current" problem of electrical power distribution for running factory machines and for ordinary domestic purposes. Such power is most economically transmitted at high voltage (E.M.F.) and relatively low current, for this enables relatively thin, and therefore cheap, wires to be used for the transmission, but it can be produced and used conveniently only at relatively low voltage and high currents. Large transformers are therefore needed at both ends of the transmission lines; "step up" transformers at the producing end which raise the voltage and reduce the current, and "step down" transformers at the consuming end, which again reduce the voltage to a convenient size, and enable high currents to be drawn out. Such transformers are often huge and expensive equipments (see plate VIII*a*) and represent a large capital outlay, so efficient design is of considerable economical importance.

We cannot go into any detail of the design problem, but an important characteristic of the ferromagnetic core of the transformer is that it should have as high a permeability as possible (that is to say, its magnetization curve should rise up to as high a magnetization as possible, which means that the saturation intensity should be high). Also the hysteresis and the *eddy current* losses in it (see below) should be as small as possible, and finally it should be cheap, since the core material represents an appreciable fraction of the whole cost of the transformer. The importance of hysteresis is that every time the alternating current in the primary coil goes through one cycle the core material magnetization goes right round the hysteresis loop of its magnetization curve. This involves a loss of energy which is proportional to the

area of the loop, and so wastes power. A similar waste of power is caused by the eddy currents induced in the core by the alternating magnetic field of the primary coil. These eddy currents can be greatly reduced by breaking up the core into laminations, electrically insulated from each, and also by using a material of as high an electrical resistance as possible.

Iron is both the cheapest ferromagnetic material and also the one with nearly the highest saturation, so it is nearly always the main constituent of the core materials for large transformers, where cheapness is all important. In order to increase its electrical resistivity, it is usually alloyed with from 2 to 4 per cent. silicon (this brings down the eddy losses). In order to reduce the hysteresis and to make the magnetization curve steep, it is essential to reduce the internal stresses as much as possible. This is achieved by annealing it at a high temperature and also by keeping it as pure as possible. One interesting modern development is to treat it in a special way (a combination of rolling it and annealing it) which makes it grow practically into a single crystal. When the treatment is successful the cube edge of the crystal is nearly along the rolling direction, and so if the sheet is magnetized in this direction, we get the nearly ideal properties of a single crystal along the cube edge.

During the last 20 years there has been an enormous reduction in the total power losses of such transformer steel sheets as a result of intensive research. From about 1·7 watts per lb. (at 50 cycles) in 1906, the total power loss has come down to 0·2 watts per lb. to-day.* A typical large transformer contains several tons of core material, so that a loss of 1 watt/lb. represents about 10 kilowatts, which would cost several hundred pounds a year. If we multiply this cost by the number

* These figures are for a maximum induction of 10,000 gauss ; the loss goes up rapidly as the maximum induction is increased.

of transformers in this country (which runs into tens of thousands), we see the economic importance of reducing the losses, since these losses are almost entirely wasted in the form of useless heat, which has to be removed by cooling with circulating water.

In "light current" engineering, the transformer problem is rather different. Here we are concerned with the small transformers such as are used in radio, and since the currents in the primary are usually very small, the saturation need not be so high. On the other hand, high permeability is very important, and it pays to use a material with as high a permeability as possible even if the saturation magnetization is low. An almost ideal material has been found in an alloy containing 80 per cent. nickel and 20 per cent. iron. Nickel is much more expensive than iron but here cheapness is a secondary consideration because the size of the transformer is small, and only a small amount of material is used. The particular suitability of this material is on account of its very low magnetostriction, and, if suitably heat treated, its internal stresses too can be made very small, so that an enormous permeability can be achieved. The hysteresis losses of this alloy are very small and since it has high electrical resistance, so too are the eddy current losses. This kind of material, of which *permalloy* is a typical example, although suitable for light current engineering, would be quite unsuitable for the large transformers of heavy current engineering, both because of its cost, and also because of its low saturation (only about a third of iron), which means that the high permeability is effective only for low magnetization.

The very opposite of magnetic characteristics are required in the hard materials used for permanent magnets. Here the hysteresis must be made as high as possible and we must get as high as possible a coercive force and remanence. We have seen that

the remanence is usually about half the saturation, but is otherwise not very dependent on the nature of the material, while the coercive force increases with the irregularity of the internal stresses. The amount of irregularity of these stresses can be greatly increased by alloying iron with certain other metals and heat treating the material in such a way that the different kinds of atoms are as irregularly arranged as possible. This can be achieved by a rather rapid cooling of the hot alloy from a high temperature, but the particular conditions depend very much on the particular alloy. In this field, progress has often been achieved by "cookery book" methods rather more than by cold scientific reasoning, though in recent years the theoretical developments outlined in this chapter and X-ray studies of atomic arrangements in various alloys have guided progress a good deal.

Before 1910, the best permanent magnets were made of glass-hard carbon steel; they were very weak by modern standards and lost their remanence very easily if shaken or heated. Then came the tungsten steels and (when tungsten was in short supply in war-time Germany), the chromium steels—alloys of iron with a few per cent. of tungsten or chromium. In 1917, the Japanese Honda and Takei found that cobalt steels were even better, but the biggest advance of all has come out of the accidental discovery in 1931 by another Japanese, Mishima, that aluminium iron alloys had good permanent magnet properties. Considerable progress has been made since Mishima's work, and modern permanent magnets are usually very complicated alloys containing iron, aluminium, nickel, cobalt, and other metals; their quality as measured by the product of the coercive force and the remanence is as much as five times better than that of tungsten steel (see fig. 35). It should be noticed that the improvement is usually obtained by a series of com-

promises, for usually in adding other metals to iron the coercive force can be increased only at the expense of reducing the remanence (which depends on the saturation magnetization). It is by no means certain that the last word has been said in the matter of improving permanent magnets, since for instance, it was recently found that an alloy of iron and platinum, suitably heat treated, had a coercive force five times as great as the best ordinary materials. Although such an alloy is ruled out for most purposes on account of the cost of platinum, it does raise the hope that there may be other suitable alloys which have not yet come to light.

5. *More about permanent magnets*

The names " hard " and " soft " applied to magnetic materials have more than a figurative meaning, for it turns out that the mechanical properties of a material are to some extent governed by the same factors which determine the magnetic quality. Thus a soft magnetic material, such as is suitable for a transformer core is actually rather soft in a mechanical sense too, and, for instance, bends easily, while the hard magnetic material of a permanent magnet is also very hard in a mechanical sense, being brittle and almost impossible to machine on a lathe. This leads to difficulties in the construction of permanent magnets. Since machining is ruled out, the magnet has to be cast into almost its final shape from the molten alloy and then ground to give it its finished form. This procedure means that not every conceivable shape of magnet can be achieved, and close contact between the customer and manufacturer is necessary in order that the customer's particular requirements may be adjusted to the manufacturing possibilities.

When a permanent magnet is first produced it is almost completely unmagnetized, and to give it its

final property of being a permanent magnet it must first be magnetized. This can be done by first saturating it in a large magnetic field, and then removing the field, so that the magnet is left with its remanent magnetization. This is usually achieved by winding a few turns of wire round the magnet and passing a huge surge of electrical current through the wire. The magnetic field of the current at its peak value is enough to saturate the material (for modern alloy magnets as much as 10,000 gauss is needed) and when the current (and its magnetic field) has died away, the material is left with its remanent magnetization (or rather less due to demagnetization effects), and is ready for use. With modern permanent magnets, the magnetism is really very permanent and is hardly affected by violent mechanical shocks, although with the old tungsten steels such shocks could reduce the magnetization very seriously. This is important in many practical uses of permanent magnets, where mechanical shocks and vibrations are unavoidable.

An interesting illustration of the way permanent magnets behave is provided by the little horse-shoe magnets which manufacturers use to advertise their wares (see plate VI*b*). These magnets are given away with a *keeper*—a small bar of ordinary iron which bridges the gap between the pole pieces. When the keeper is in place the whole magnet forms a closed ring, and if it is magnetized with the keeper on, the full remanence is achieved, for there are no poles anywhere to produce a demagnetizing field. In this state the keeper is held on very tightly and a considerable force is needed to pull it away (this force is estimated in Chapter 8, and amounts to several pounds), thus displaying what the permanent magnet can do.

Once the keeper has been pulled off, however, the demagnetizing field of the exposed poles comes into play and the magnetization of the magnet falls off—

we move in fact from A to B on the characteristic curve of the material (fig. 44). If now the keeper is replaced the demagnetizing field is destroyed, but there is some hysteresis and the magnetization follows a lower

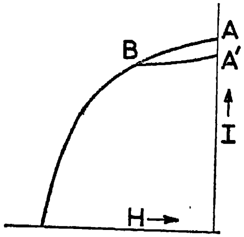


Fig. 44.—When the keeper is removed from a permanent magnet which has been magnetized with the keeper in position, the magnetization drops from A to B, owing to the demagnetizing field of the open poles. If now the keeper is restored the magnetization rises again but only to a value A′ lower than A.

curve and returns only to A′ below A. The keeper can now be pulled off with rather less force, and this is quite easily felt without any special measuring device. This simple experiment brings out an important point in magnet construction. In many uses of permanent magnets various pieces of ordinary iron are involved, bridging as much of the air gap between the poles as is permitted by the detailed design, in order to reduce the demagnetization effects as much as possible. Now, in order to achieve the strongest possible magnetization, it is essential that the magnet should be magnetized with all these iron pieces in their final positions, for otherwise only a lower magnetization (such as A′) will be obtained. Once the whole arrangement has been fully magnetized, it must not be taken to pieces and re-assembled or else the magnetization will suffer.

In conclusion, we may mention some other pretty demonstrations of the power of modern permanent magnets. As has already been explained, the importance of the high coercive force of a modern permanent magnet is that it permits the use of a shape with a relatively large demagnetizing effect, without reducing the magnetization as much as would happen with lower coercive force. This means that a rather short and thick bar magnet can be made with high pole strength, or more technically, the ratio of pole strength to weight can be made very high in a modern magnet. Consequently magnets can be made so strong in relation to their weights, that the repulsive force between two magnets when they are placed one above the other with like poles nearest each other, is enough to hold the upper magnet floating quite high above the lower. The upper magnet must move in vertical guides or else it will swing round and be attracted instead of repelled, and fig. 45 illustrates a

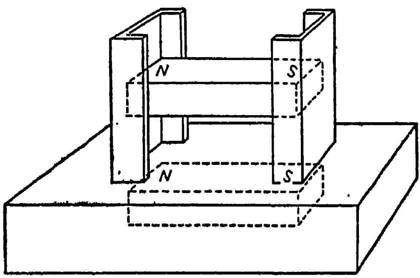


Fig. 45.—The floating magnet trick: a modern version of Mahomet's coffin.

typical arrangement for demonstrating this modern version of "Mahomet's coffin." In some variants of this floating magnet trick, the lower magnet is concealed

so that to the uninitiated the floating appears quite mysterious.*

Another trick with two short magnets is illustrated in fig. 46. If one of the magnets has a rectangular cross-section it can, if placed with an edge on a rough

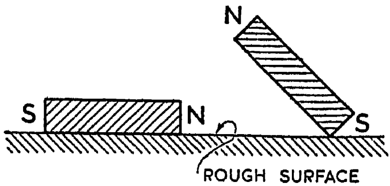


Fig. 46.—The nodding magnet trick.

surface, be made to tilt up in the way shown (friction at the supporting edge prevents it turning round, if the magnet is carefully manipulated). If slightly disturbed, it rocks about its equilibrium position in a very amusing fashion. We may mention also a trick with a strong horse-shoe magnet; if the magnet is made to attract its keeper through a handkerchief or a piece of paper and is then pulled along this surface, it drags its keeper along with it, in a series of jumps, the keeper turning over and over as it moves along. Try it and see.

One final word of warning: if you should really try any of these tricks, or for that matter any other experiment which brings you into a strong magnetic field, first remove your watch. The hair spring can easily become magnetized if brought into a field, and since it

* Since this was written, an even more striking version of "Mahomet's coffin" has been demonstrated by Arkadiev in Moscow (and reproduced also in Cambridge). If a small powerful magnet is released over the surface of a superconducting trough (see Chapter 4, p. 105), it floats in the liquid helium which keeps the superconductor cold, owing to the repulsive force produced by the diamagnetism of the superconductor.

is usually made of a hard steel, it will subsequently retain some magnetization which can quite upset the time-keeping of the watch. If this should happen, the trouble can be repaired by hanging the watch on a thread, spinning it in a coil through which alternating current passes, and slowly withdrawing it. The alternating magnetic field of the coil, which disappears smoothly as the watch is withdrawn, is applied to the spring in all possible directions (by the spinning motion) and removes the retained magnetization very effectively.

Chapter Six

THE EARTH'S MAGNETISM

1. *The Earth's magnetic field*

IT is the magnetism of the earth which makes possible the use of a compass needle for navigation—the first practical application of magnetism, and much of the early scientific work was concerned with clarifying the nature of this terrestial magnetism. More recent work has shown that it is important not only in this particular practical application, but also in such apparently unconnected topics as wireless transmission, the behaviour of cosmic rays and prospecting for minerals. In this chapter we shall deal mainly with the fundamental aspects of terrestial magnetism, leaving the practical applications to the following two chapters. We shall try to give the answers to such questions as how strong is the earth's magnetism, how it varies from place to place and with the passage of time, and to what extent other heavenly bodies, such as the sun and the stars, show a similar magnetism.

The invention of the mariners' compass cannot be very clearly traced, but already in the 11th century the Chinese, Shen Kua, wrote a very clear account of the remarkable properties of a " south pointing needle " floated in water on a bamboo stalk*. He was not only aware of its property of pointing in a definite direction, but also that this direction was not exactly north and south, and he gives a precise statement as to the size of this declination (see p. 140). Probably

* Since this was written, new historical research has shown that probably the Chinese used the compass many hundred years before this.

the compass was known and used well before this first documentary evidence, but it is not, as is sometimes said, the same as the "Chariot of the South" first mentioned in a Chinese document of A.D. 100. This would indeed be an appropriate name for the magnetic compass, and Kipling makes use of it in "Puck of Pooks Hill," but historical research proves that the "Chariot of the South" was some sort of mechanical contrivance which made no use of magnetism at all.

From China, knowledge of the compass soon reached Europe, probably through the medium of the Arabs, who were the great seafarers of that time, and in 1187 Alexander Neckham of St. Albans had already described the use of a compass for navigation. Much more detailed documentary evidence of knowledge about the compass occurs in a letter from Peter Peregrinus to a friend in 1269. Peregrinus was one of the first scientists of the modern school, who preferred experiment to speculation; he had been a pupil of Roger Bacon in Paris, and Bacon said of him : " what others see dimly and blindly, like bats in twilight, he gazes at in the full light of day, because he is a master of experiment." In his letter he describes how a sphere of lodestone, if floated on water, always sets itself north and south " and if this stone be moved aside a thousand times, a thousand times will it return to its place or position by the direction of God." He also showed that if a steel needle was brought close to his lodestone sphere, it set along a definite direction, and the lines along which it set, if joined up, traced meridians on the sphere, meeting at two points (which we now call the magnetic poles).

Much later, in 1600, William Gilbert, who was physician to Queen Elizabeth, considerably extended Perigrinus's observations and interpreted them. In his treatise " De magnete " he correctly inferred from his experiments that since a compass needle set itself approximately along lines of longitude on the earth's

surface, the earth must itself be a magnetized sphere, a large scale version of Peregrinus's lodestone sphere.

This idea that the earth is a magnetized sphere, forms a convenient starting point for answering our questions about the strength of the earth's field and its variation from place to place. It can be shown mathematically that a uniformly magnetized sphere has a magnetic field outside itself which is exactly the same as the field of a magnetic dipole placed at the centre of the sphere, provided this dipole points the same way as the sphere's magnetization and has the same magnetic moment. The field of such a dipole is exactly calculable, and it is found that if its strength and direction are correctly chosen, it does indeed roughly reproduce the actual magnetic field at the earth's surface, and its variation with geographical position. To define a magnetic field at any place completely, we need to specify three quantities, because of the vector character of a field, and these quantities can be chosen in various ways. We may, for instance, specify the magnitude of the field and two angles to define its direction, or (as is more usual) the horizontal and vertical components of the field, and the direction of the horizontal component in a horizontal plane.

The field at the earth's surface of a dipole placed at its centre is easily calculated; if M is its magnetic moment, then the horizontal component, H, and the vertical component, V, are given by

$$H = M \cos \theta / a^3 \qquad V = 2\, M \sin \theta / a^3$$

where a is the radius of the earth, and θ is the *magnetic latitude*. Before going on, a word of explanation is necessary about the meaning of magnetic latitude. The magnetic poles of the earth (where the direction of the dipole meets the earth's surface) are not exactly at the geographical poles (where the axis of the earth's rotation meets the earth's surface). The magnetic latitude is just the angle round the earth's surface from

the *magnetic equator* (the great circle equally distant from the two magnetic poles) ; this is slightly different from the geographic latitude (see fig. 47).

As we shall see in a moment, all the magnetic

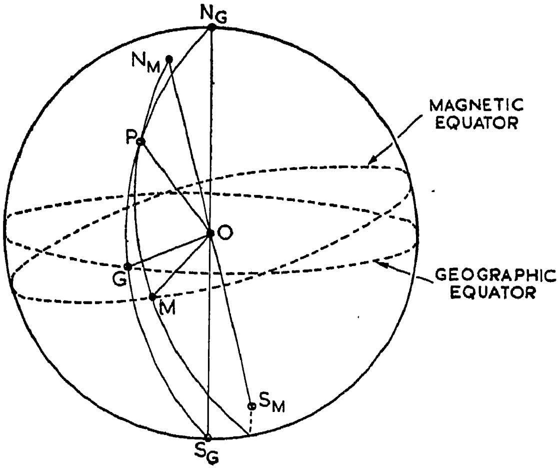


Fig. 47.—The geographical poles are at N_G and S_G, the magnetic poles at N_M and S_M (but note that N_M is really a south, and S_M a north magnetic pole, if the earth is regarded as a magnet). The *magnetic equator* is a great circle perpendicular to the polar axis N_MS_M (N_MOM is a right angle), just as the geographic equator is perpendicular to N_GS_G (N_GOG is a right angle). The latitudes of any point P are defined by the angles POG which gives the geographic latitude and POM which gives the *magnetic latitude*. The curves through P are great circles each of which passes also through one pair of poles. *Longitude* is measured by the angle which the plane of such a great circle makes with the plane of a fixed great circle passing through Greenwich.

characteristics of the earth are slowly changing, and the exact positions of the magnetic poles change slowly too; Amundsen in 1904 was the first to locate the magnetic north* pole and he found it at Felix Boothia (geographical latitude 70°N and longitude 97°W) by observing that a magnetic compass showed no preference for pointing in any particular direction at that place. A recent survey (1945) by the R.A.F. taking observations from the Lancaster "Aries" aeroplane, has shown that the pole has shifted about 300 miles N.N.W. and is now in Bathurst Island, so we must bear in mind that magnetic latitude at any place is not a fixed quantity, but changes appreciably even in a single lifetime.

Coming back to our formulae for H and V, let us see what they mean in practice by working out some simple examples. The magnetic latitude of London at present is about 54° (slightly different from the geographical latitude, which is 52°), and if we put $M/a^3=0{\cdot}32$ gauss (this turns out to be the best value to choose) we find for London, $H=0{\cdot}32 \cos 54°=0{\cdot}19$ gauss and $V=0{\cdot}64 \sin 54°=0{\cdot}52$ gauss†. At the magnetic equator, where $\theta=0$, $H=0{\cdot}32$ gauss, while $V=0$, and at the north magnetic pole, where $\theta=90°$, $H=0$, while $V=0{\cdot}64$ gauss. Thus, as we go up from

* The nomenclature here is a little confusing, for actually as pointed out in the caption to fig. 47 the magnetic pole which is close to the geographic north pole is really magnetically a south pole, since it attracts the north pole of a compass needle. The word north in the text is used in the geographic sense. A further complication is that the exact position of the magnetic pole depends on whether the irregularities of the earth's field are considered or not. Thus if the earth were really a uniformly magnetized sphere, the north and south magnetic poles should be diametrically opposite, while actually the south magnetic pole (first located by Mawson and David in 1908) is at about 72°S and 154°E. We shall, however, ignore such complications to avoid confusion.

† Actually, the measured values are $H=0{\cdot}19$ gauss and $V=0{\cdot}43$ gauss; the discrepancy in V is again due to the roughness of the assumption that the earth is a uniformly magnetized sphere.

the magnetic equator to the north magnetic pole, the horizontal component falls off steadily from its highest value, 0·32 gauss to zero, while the vertical component increases steadily from zero to its highest value, 0·64 gauss. Notice, too, that the earth's field does not depend on the *magnetic longitude* (though, of course, it does depend slightly on geographical longitude, because the magnetic latitude varies slightly as we go geographically east or west from any point. The strength of the earth's total field is given by $\sqrt{H^2+V^2}$ (from the usual rules of vector addition) and is about 0·56 gauss in London; its biggest value is 0·64 gauss at the north magnetic pole, where it is entirely vertical, and it is least at the magnetic equator where it is 0·32 gauss and entirely horizontal.

The fact that there is a vertical as well as a horizontal component of the earth's field means that the resultant magnetic field points at an angle to the horizontal. Thus if we arrange a carefully balanced magnetized needle so that it can rotate in a vertical plane (as distinct from the usual compass needle which is arranged to rotate in a horizontal plane), the needle of this *dip-circle*, as it is called, will come to rest at an angle to the horizontal. If the plane of the dip-circle is twisted to point to the magnetic north (or in other words is placed in the *magnetic meridian*), the needle actually points along the resultant direction of the earth's field, and its angle to the horizontal is called the *dip angle*. This dipping of a magnetic needle was first discovered by Robert Norman in 1576, even before Gilbert had pointed out that the earth was a magnetized sphere (once this is assumed, the dip is an obvious consequence).

The dip angle is easily calculated if we know H and V, for if the dip angle is ϕ, then

$$\tan\phi = V/H$$

From our formulae for H and V, we see that:

$$\tan\phi = 2\tan\theta$$

Since for London $\theta=54°$, we have that the dip angle in London should be that angle whose tangent is twice the tangent of $54°$, and this comes out to be $70°$. Alternatively we could have obtained the same result from the numerical values $H=0{\cdot}19$, $V=0{\cdot}52$, which gives $\tan\phi=2{\cdot}74$, and again $\phi=70°$*. It should be noticed that the dip angle increases steadily from zero at the equator to $90°$ at the north magnetic pole.

The direction of H, the horizontal component of the earth's magnetic field, is towards the north magnetic pole, so that a horizontal compass needle (which, of course, sets itself along the direction of H) does not point exactly to the geographical or *true north*, but at a slight angle to it. This angle between the direction of H and the true north is called the *declination* or *variation*. It is evidently very important for navigation, because only when it is known at every place, can the reading of a compass be properly corrected to show which direction is true north. In principle, the declination could be calculated by spherical trigonometry if we knew exactly where the magnetic poles of the earth were located, but actually the calculation is not worth while, because our basic assumption that the earth is a uniformly magnetized sphere is only roughly true, and the approximate nature of the assumption makes the results of such a calculation very inaccurate. Instead, the declination is found by direct measurement of the angle between the magnetic and true north at very many places, and charts are constructed on which places of equal declination are joined by so-called *isogonic lines*, rather like the contours of equal height on an ordinary map. A typical isogonic chart is shown in fig. 48, and if the navigator knows his rough position, he can read off the approximate declination from the chart and so

* The actually measured value of ϕ, corresponding to the actual values of H and V (see previous footnote) is about $67°$.

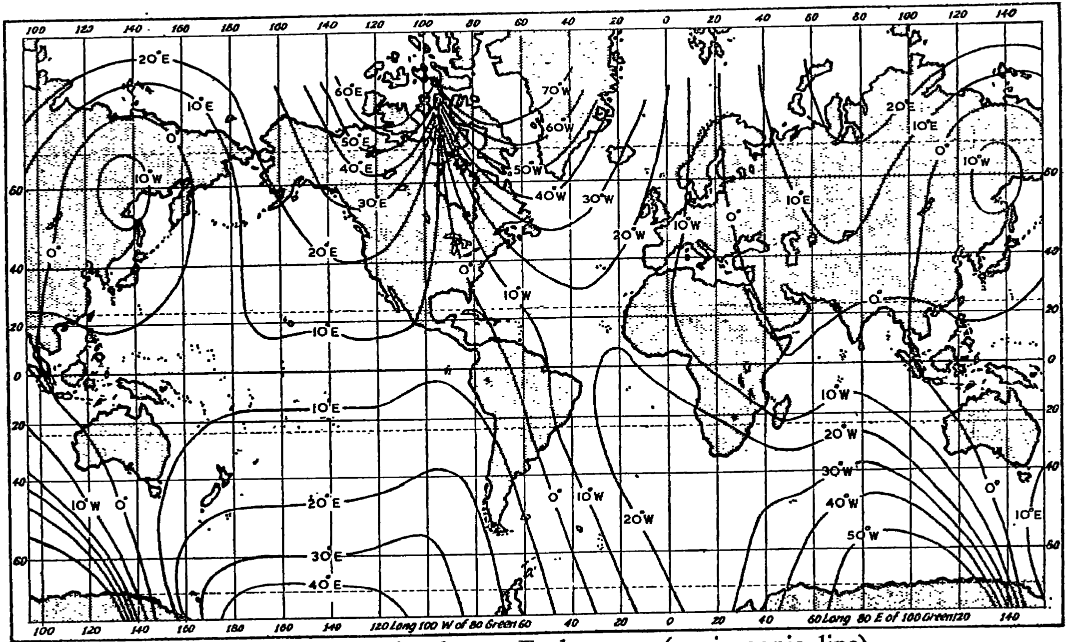


Fig. 48.—Isogonic chart. Each curve (an isogonic line) corresponds to a certain value of declination (marked on it).

deduce the true north direction from his compass reading and decide which way to steer his ship.

As we might expect, the declination gets smaller as we go further away from the poles, but even in England, it is not by any means negligible, being about 11°W in London at the present time. Near the magnetic poles the declination can be very large and varies rapidly with position, for evidently if we travel in a small circle round the north magnetic pole, the declination will vary from zero, when we cross the geographical longitude of the magnetic pole on the south side, to 180° when we cross the same longitude on the north side (at this place a compass needle would point just opposite to the true north). A great complication in navigation is that the declination changes slowly with time; thus the declination in London has decreased steadily from about 24½° West in 1815 to its present value of about 11° West. This means that isogonic charts must be brought up to date every few years if they are to be of much use for reliable navigation.

2. *The origin of the earth's magnetism*

In order to answer the next question, about the origin of the earth's magnetism, we return again to the question of its magnitude. We saw that, to make calculation agree with observation, we had to choose $M/a^3=0{\cdot}32$ gauss. Now, the radius of the earth is $6{\cdot}4 \times 10^8$ cm. (about 4,000 miles), so we get for M, the strength of the dipole which would give a field at the earth's surface equal to that actually observed, a value of about 8×10^{25}. Observations at the surface of the earth cannot tell us whether this huge dipole is really concentrated at the centre of the earth or whether it is spread uniformly through the volume of the earth (if the earth were uniformly magnetized). Actually, it is very unlikely that it can really be concentrated

at the centre, because, as we saw in Chapter 4, the highest intensity of magnetization of any material is about 1,600 per cc., so the magnetic moment of the earth to have its huge value of 8×10^{25}—would have to occupy a volume of at least 5×10^{22} cc. which corresponds to a sphere of radius at least $\frac{1}{30}$ of the earth's radius. If, on the other hand, the magnetization was uniformly spread through the earth's volume, the intensity of magnetization would have to be about 0·07.

At first sight this seems a reasonable enough supposition, but again more detailed considerations raise great difficulties. Direct experiment shows that the surface layers of the earth are not magnetized to anything like an intensity of 0·07, and moreover it is known that the temperature rises rapidly as we go into the interior of the earth, which makes it unlikely that the magnetization will be higher there (since ferromagnetic magnetization decreases with temperature rise, as we saw in Chapter 4). An ingenious suggestion to explain away the difficulty is to invoke the pressure increase which occurs towards the interior of the earth. It has been suggested, in fact, that the molten core of the earth contains a great deal of iron or other ferromagnetic material, which, on account of the high pressure, has a much higher Curie temperature than ordinary ferromagnetics, and so is able to retain the required intensity of magnetization. Unfortunately, laboratory experiments, as far as they go, show that the pressure effect works the wrong way, lowering rather than raising the Curie temperature. So if this suggestion is not to be discarded, we must suppose that the trend observed at the relatively low pressures attainable in the laboratory, reverses at the much higher pressures in the interior of the earth—but this is mere guesswork, since there is no theoretical reason for such a reversal.

A quite different, though almost equally speculative attempt to explain the earth's magnetism is to suppose that it is due to electric currents circulating round the earth's axis in the interior of the earth. No very convincing explanation has been worked out of how such currents might have started, and it is difficult to see why they do not decay fairly rapidly due to the electrical resistance of the earth's core. Now there is actually some evidence suggesting that the magnetic moment of the earth (and so also the earth's field) has decreased by about 3 per cent. during the last hundred years and, if this decrease is put down to decay of the hypothetical electrical currents, we can estimate what the electrical resistance of the earth's core would have to be. The calculation shows that it would have to be much lower than it is actually known to be for the outer layers of the earth, so again we must either make the *ad hoc* assumption that conditions in the interior of the earth are very different from those in the outer layers, or assume that the currents are partially prevented from decaying by some other mechanism.

Another difficulty arises if we follow the electric current idea in its simplest form to its logical conclusion; for if the currents have decayed by 3 per cent. in the last hundred years, it is easy to see that they must have been much larger still longer ago. The decay follows what is called an exponential law, and we can deduce that two thousand years ago the earth's field would have had to be twice as big as it is now, while a million years ago (and it is known that the earth is certainly older than this) it would have been astronomically large—a number with more than a hundred zeros after it! This is fantastically improbable if only because the enormous currents producing this field would have generated more than enough heat to vaporize the earth. We must suppose then, either

that the currents started circulating only comparatively recently—say some tens of thousands of years ago, or that they are not really decaying according to an exponential law.

Various ingenious theories have been proposed to account for a continuous maintenance of the currents, invoking mechanisms based on the earth's rotation, but they are all too speculative to carry much conviction. So after all, there seems to be no very good answer as yet to our question about the origin of the earth's magnetism. There are almost equal difficulties in supposing the basic cause is permanent magnetism within the earth's core or that it is electric currents circulating inside the earth. Probably the balance of evidence is slightly in favour of the electrical theory, but much still remains to be done before this riddle, one of the oldest still left obscure, can be regarded as solved.

3. *Departures of the earth's field from that of a uniformly magnetized sphere*

Up to now we have considered the earth's magnetism as if it could be entirely described in terms of a uniformly magnetized sphere (or an equivalent dipole at its centre), but this is by no means the whole story. First of all, there are considerable irregularities of the field as we move from one place to another, as well as the smooth variation to be expected from a uniformly magnetized sphere. These are due to a variety of causes; there are gradual irregularities due to the earth not being exactly spherical and not being exactly uniformly magnetized, and there are local irregularities due to the presence of magnetic ores close to the earth's surface (these latter irregularities are of importance in prospecting for oil and minerals, as we shall explain in Chapter 8). It is these irregularities, and particularly the gradual ones, which are

responsible for the rather irregular nature of the isogonic chart (fig. 48), for if the earth were exactly spherical and exactly uniformly magnetized, the isogonic lines would be exactly calculable, and would have a much more regular appearance.

Quite another kind of irregularity is that the earth's magnetism also varies with time, and varies, moreover, in a very complicated fashion. We have already mentioned that there is a slow variation with time, both of the magnitude of the field and of its direction. This slow time, or *secular variation*, as it is called, has been known for a long time; Henry Gellibrand of Gresham's College in London first noticed the slow variation of declination in 1634, the slow variation of dip was also discovered in the 17th century, and that of H and V themselves (and therefore of M) dates from the last century. It is very likely that these secular variations are associated with the same causes that are responsible for the main field, and their origin is as much of a mystery as is the main part of the magnetism itself.

More careful measurements in recent times have shown that in addition to these secular changes there are also more rapid variations of the field with time. These changes are very small (usually only a few parts in a thousand of the main field, or less) but have proved very important from a scientific point of view. A detailed analysis of the earth's field as a whole has shown that a few per cent. of it must be attributed to causes *outside* the earth, and it proves that the small variations with time of a more rapid kind are mainly associated with these external causes. Recent work on wireless transmission has provided the clue to the nature of these external causes, and also their time variation.

It has been shown that there are several electrically charged (or *ionized*) layers, high up in the earth's

atmosphere and these layers affect wireless waves in much the same way as a glass prism deviates a beam of light. The wireless waves get bent downwards as they enter a layer of this kind and are able to reach the earth again at great distances from the transmitter. It is this bending effect which makes possible wireless reception from distant places, for without it we could receive wireless waves only from nearby transmitters, as is shown schematically in fig. 49; the waves that went into the air from the transmitter would be lost

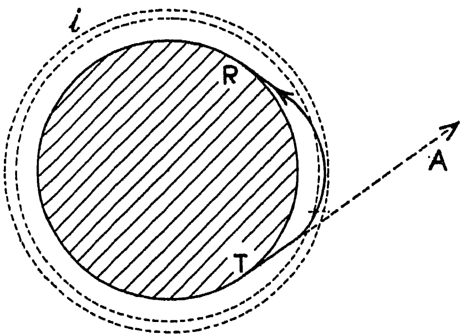


Fig. 49.—The bending effect of the ionosphere. A wireless wave leaving the transmitter T on the earth's surface, would travel along the straight line A if it were not for the bending effect of the ionosphere, *i*, which directs it to a receiver R, which may be several thousand miles away, and could not otherwise be reached.

in empty space. These charged layers behave in a very complicated way, for their strength and height depends on such factors as the intensity of the sun's ultra-violet rays (which produce electric charge by a process known as *ionization*), and this complicated behaviour

is responsible for the uncertainties in reception of wireless signals from distant places (for instance, rapid changes in the layers cause wireless " fading "). Now we know that movement of electric charge produces a magnetic field, so it is natural to associate the " external " part of the earth's field with motion of the electrically charged layers which are so important for wireless transmission. Detailed investigation supports this interpretation, and is able to account roughly for the time variations as well.

Several different kinds of time variation are revealed by very careful analysis of simultaneous magnetic measurements at several magnetic observatories taken continuously over many years. Broadly speaking, they can be divided into a variation which repeats itself with a daily period, and irregular disturbances, changing from hour to hour, which are superimposed on the smooth daily variations. The irregular disturbances when sufficiently strong are called *magnetic storms* and we shall return to them directly.

The smooth daily variations are clearly associated with rotation of the earth about its axis, and are partly due to the daily variation of the amount of sunlight falling on the earth at any place. This " solar " part of the daily variation shows seasonal changes corresponding to the movement of the earth round the sun, which is just as we should expect on this interpretation. A smaller part of the daily variation is connected, however, with the moon, since its size is found to vary regularly with the 28-day period of rotation of the moon round the earth. It is probable that this " lunar " part of the variation is due to tidal motion of the ionized layers, similar to the tides produced in the oceans by gravitational attraction from the moon.

Another interesting feature of the daily variation (both solar and lunar) is that if its size is averaged over a whole year, it is found that this average varies with

something like an eleven-year period. It seems in fact to be closely connected with the *sun-spot activity* of the sun. Examination of the sun shows up a number of "spots" on its surface which are appreciably darker than the general background. These sun-spots seem to move about the sun's surface and to appear and disappear in a very irregular way, but if their average strength or sun-spot activity is studied, it is found to go through a cycle which repeats itself roughly every eleven years. All sorts of unexpected natural phenomena seem to respond to this eleven-year period—for instance, the height of the surface of Lake Victoria (in Africa) varies with an eleven-year period, and the annual rings in tree trunks show a variation in appearance which repeats itself every eleven rings. It has even been suggested that the cyclic variations of booms and slumps in world economics are connected with the sun-spot cycle (it is, however, simpler to explain them in terms of our inability to manage our affairs sensibly).

The earth's magnetism is no exception to this eleven-year periodicity, and the correlation here is remarkably close, as shown by fig. 50, in which the daily "range" (the size of the daily variation) of H, averaged over each year, and the average *sun-spot number* (a measure of the sun-spot activity) are plotted side by side against the years from 1894 to 1905. The probable explanation of the correlation is that the sun-spot activity has a big effect on the ultra-violet light intensity and other agents (see next paragraph) reaching the upper atmosphere, and this affects the height and strength of the charged layers whose motion is responsible for the "external" part of the earth's magnetic field. This explanation is supported by corresponding changes in the layers as observed by wireless methods.

The sun-spots have a very close connection with the

irregular part of the time variation too. Just as the average daily variation of the earth's field is closely connected

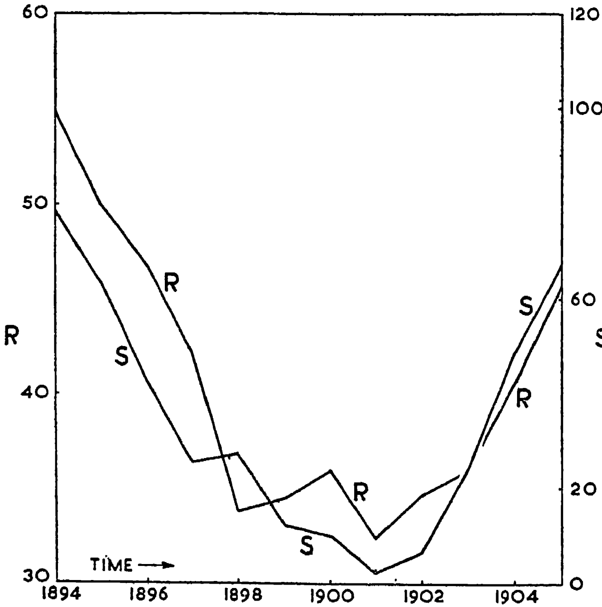


Fig. 50.—Curves showing how the daily range, *R* (a measure of the daily variation of the horizontal component of the earth's field), and the sun-spot number, *S*, varied at a particular station from year to year between 1894 and 1905. The similarity of the curves indicates the close relation between sun-spot activity and the earth's magnetic field. Note that after eleven years both *R* and *S* have returned nearly to their original values.

with the average sun-spot activity so, too, the irregular variation is closely connected with the irregular changes of sun-spot activity. The nature of the correlation is

very complicated but we may mention two interesting features. The first of these features provides rather convincing evidence that any particular magnetic storm is probably associated with a particular group of sun-spots on the sun's surface. Chree, in 1912, found from careful analysis of magnetic storms that they tend to recur with a period of 27 days, which just coincides with the period of rotation of the sun about its own axis.* This suggests strongly that it is some particular area of the sun's surface which is responsible for the storm, and this area is affective only when it faces the earth; as the sun rotates, the area becomes ineffective until about 27 days later when it again comes into the right position to cause a magnetic storm.

The second feature is that there seems to be a time lag of about a day (this interval is rather variable, however) between an increase of sun-spot activity and the incidence of a magnetic storm on the earth. This suggests that the sun-spots† emit some sort of particles which take a day to travel from the sun to the earth's atmosphere. Since the sun is 93 million miles away, this means that the particles must have speeds of several hundred miles a second. When they arrive in the earth's atmosphere they cause

* Actually, a similar effect of the sun's rotation on the smooth daily variation has been known since 1871, when Hornstein discovered a feeble 27-day periodicity in the size of the ordinary smooth daily variation of the magnetic field. Maxwell said of this discovery: " this method of discovering the rotation of the unseen solid body of the sun is the first instalment of the repayment by magnetism of its debt to astronomy " (though now it seems more likely that the effects are due to the visible sun-spots, rather than to the invisible solid core of the sun).

† Recent work has shown that it is probably *solar flares* (brilliant patches of light which appear close to sun-spots, and last only 20 minutes or so) which emit the particles. At the moment the flare appears a slight magnetic irregularity is recorded (probably due to the ultra-violet light effects), but the magnetic storm occurs only about a day later. For further details see *Frontiers of Astronomy* by D. S. Evans (p. 122).

modifications of the electrically charged layers, by increasing the ionization, and so produce the magnetic storm. The idea of corpuscular emission by sun-spots fits in well with another observation, namely that not every sun-spot is found to cause a magnetic disturbance. In many cases the sun-spot will never face the right way to discharge its particles on to the earth, and then, of course, no storm is produced.

Just as before, there is a close correlation between effects in wireless transmission and magnetic storms. All sorts of anomalies occur during and just before a magnetic storm, and wireless reception from distant transmitters becomes very irregular and uncertain. This again shows that the magnetic effects arise from the same ionized layers which play such an important part in wireless transmission. A particularly serious example of this kind of disturbance, or *radio fade-out* as it is called, occurred recently (Sept., 1946) and may have been the cause of the crash of a Belgian air-liner in Newfoundland; much of modern air navigation depends on wireless methods, and a radio fade-out can have disastrous consequences.

4. *Magnetism in the Universe*

If the earth is a huge magnet, may not other heavenly bodies too be magnets? Only in one case, that of the sun, is it possible to give an answer, and this answer is in the affirmative, though not very definitely. The evidence for this answer is rather indirect, but very ingenious. The sun is so far away that, although it probably has a magnetic moment very many times larger than that of the earth, its direct effect is quite negligible. This is because the magnetic field of a spherical magnet falls off as the cube of the distance from its centre, so since the earth is about 230 times as far away as the sun's radius, the field of the sun at the earth must be about $230 \times 230 \times 230$, or roughly

12 million times smaller than it is at the sun's surface. It is in fact too small to be detectable against the background of the irregular changes in the earth's own magnetic field.

The indirect way which has shown up the sun's magnetic field is based on what is known as the *Zeeman effect*, a change in the wavelength of light when it is emitted in a magnetic field. If white light is examined by means of a *spectroscope*, it is split up into a *spectrum* of colours ranging from red to violet (different wavelength means different colour). Included in the spectrum are also a number of sharp lines of very definite wavelengths and it is found that these are characteristic of certain atoms in the hot body which emits the white light. Now laboratory experiments have shown that if the light source is placed in a magnetic field, these lines " split up " in a manner which is too complicated to explain here. By " splitting " we mean that each line separates out into a small group of lines. The wavelength differences between the members of this group prove to be proportional to the magnetic field strength and are easily measurable for fields of a few thousand gauss or more. With the very powerful spectroscopes, developed in recent times, it is possible to detect the splitting caused by fields of only a few tens of gauss, but this is about the limit, since for smaller fields the splitting becomes too small to measure.

There is no need to go into the explanation of this splitting effect, named after Zeeman, who first studied it about 50 years ago, though it is worth mentioning that it is closely linked with the theory of paramagnetic behaviour. However, it is evident that it can be used to measure an unknown magnetic field if it exists at a distant source of light. If we assume that the atoms in the source (for instance, the sun) behave in the same way as atoms in the laboratory, and this is a very

reasonable assumption, we can deduce from the observed splitting the magnetic field which is present in the source.

The American astronomer Hale, found that over most of the sun's surface there is a magnetic field of about 50 gauss, just large enough to be detected by this method, but other astronomers have not been able to repeat his observation, and it is possible that the field is smaller than Hale supposed. If, however, the spectroscope is pointed towards a sun-spot, a much larger Zeeman effect is observed, corresponding to a field of as much as 3,000 gauss. This gives a useful clue to the nature of sun-spots, for a field as large as this can probably be due only to some sort of violent motion of electric charges.

It is likely, in fact, that a sun-spot is a kind of whirlpool of electric charges ; but just as there are great difficulties in working out the cause of the earth's magnetism, so here, too, there is considerable controversy among the theoreticians as to just how such whirlpools come to being. An interesting feature of the magnetic field of sun-spots is that the direction of the field is opposite in pairs of sun-spots close together. It is as if the rotating changes were confined to a curved column which entered the sun at one sun-spot and emerged at the other (the field at the two ends is then opposite, just as it would be at the two ends of a solenoid bent into a half circle).

When we come to heavenly bodies other than the sun, such as the stars, the Zeeman method of discovering magnetic fields breaks down. This is simply because the light from a star is usually too feeble to bear spreading out into a spectrum broad enough to reveal Zeeman splitting. It is only with brilliant sources like the sun that the intensity is adequate to permit such high resolution as is necessary to detect weak magnetic fields. It is, however, improbable

that the earth and the sun are the only magnetic heavenly bodies, and there is every reason to expect that all stars behave like magnets.*

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* Since this was written, the surface magnetic fields of a number of stars have been measured by Babcock in the U.S.A. and others, using a very sensitive method based on the Zeeman effect. For the star 78 Virginis, the surface magnetic field was found to be about 1,500 gauss. On the basis of such measurements and the known fields of the earth and the sun, Blackett has revived an old theory of Schuster in which it is suggested that *any* rotating body has an intrinsic magnetization associated with its angular momentum in a fundamental but unexplained manner. Although this theory has the attraction of bypassing the difficulties discussed on p. 142, it is still the subject of lively discussion and new experimental results must be awaited before a final verdict is possible.

Chapter Seven

MAGNETISM AS A TOOL IN SCIENCE

1. *Famous magnets in the world's laboratories*

FOR almost any scientific application of magnetism the first requisite is a magnetic field, and for many purposes it is important to produce as strong a field as possible in as large a space as possible. How can this be achieved? Until the 19th century the only means known was to use a permanent magnet such as the lodestone. This, however, is a comparatively limited method, for it is limited by the magnetic properties of the material of the magnet. Even using the most powerful magnet steels such as described in Chapter 5, it is hardly possible to obtain fields much beyond 10,000 gauss.

For many purposes this limitation is not important, and then the permanent magnet has the great advantage of simplicity, since no electrical supplies are required. For instance, in the magnetron valve (see p. 176) a permanent magnet is very convenient, especially if the magnet is part of an airborne radar equipment, where the relatively light weight of the magnet is an advantage. Another important use of permanent magnets is in electrical measuring instruments, where again the limited size of field is not serious, but compactness is desirable. The permanent magnet is usually made in the form of a nearly closed ring, rather like a horseshoe, because this reduces the demagnetizing effect, and increases the field in the gap. Some typical magnets of this kind are illustrated in plate VI. By partly bridging the gap of a permanent magnet with soft iron

pole pieces the field can be increased, though of course only at the expense of reducing the space in which the field acts. If a given field is required over a larger region the dimensions of the whole magnet must be scaled up accordingly.

An extreme example of the application of this principle is the 70-ton permanent magnet used by Rosenblum at Bellevue, near Paris (in the same laboratory which houses the famous electromagnet described on p. 162) for measuring the speeds of the *α-rays* emitted by radioactive substances. The girl in the illustration (plate VI) is standing close to the pole piece gap in which the speed-measuring apparatus is placed. The principle of the apparatus is similar to that of the β-ray spectrograph (see fig. 52), but since the α particles are much heavier than electrons (β-rays) they are not bent nearly as much by the magnetic field, and so the magnetic field must extend over a much larger area to produce the same effect. It is for this reason that such a huge magnet is needed. Blocks of permanent magnet material are mounted above and below the soft iron pole pieces, and the "magnetic circuit" is completed by the huge soft iron rings. The coils which can be seen in the illustration wound round the permanent magnet blocks are used to magnetize them; once this has been done the field in the gap stays constant without any power expenditure.

With the discovery of the magnetic effect of electric currents, other types of magnets became possible. Apart from the possibility of obtaining stronger fields, such *electromagnets* have the advantage of flexibility over permanent magnets. The field can be varied by altering the electric current, which is not possible with an ordinary permanent magnet. The simplest electromagnet is the solenoid (p. 30) in which the magnetic field is just directly proportional to the electric current and the number of turns per unit

length. The great drawback of the solenoid is that the electric current generates heat in overcoming the resistance of the solenoid coil and, unless some provision is made to remove this heat, the solenoid may get dangerously hot. Without any special arrangements, this heating severely limits the fields that can be obtained, and in practice little more than 2,000 gauss can be obtained for any length of time without the temperature rising sufficiently to burn the insulation of the wire.

How can this limitation be overcome? First of all the wire should be made of a material with as low as possible an electrical resistance. In practice copper is almost the only suitable material, though silver is slightly better and in special circumstances the extra expense may be worth while (see p. 169). Still lower resistance can be obtained by cooling the copper; as for instance with liquid air (when the resistance is about seven times lower), but this is usually impracticable since enormous quantities of liquid air would be boiled away by the heat produced. The obvious way of dealing with the difficulty is to remove the heat by water cooling. If water is passed sufficiently rapidly through the coils and in sufficiently intimate contact with them, very great power can be dissipated without a dangerous rise of temperature.

This method has been pushed very far by Bitter at the Massachussetts Institute of Technology. His solenoid is of a special design and consists effectively of a flat copper spiral; each turn of the spiral is a flat annulus, insulated from the next turn by thin mica spacers. All the annular turns of this spiral are perforated with many small holes, so that large quantities of water can be pumped through the whole coil in the direction of its axis. In this way it is possible to use a power as high as 1,000 kW. without dangerous heating, and a field of 100,000 gauss is obtained over a fairly large volume.

Ashmead in Cambridge has also constructed water-cooled solenoids of this kind, though his coil design is more conventional, with the water passing through spaces between the turns of wire in the coil (see plate V). Such magnets are fairly easy and cheap to build, but they are expensive to run : Ashmead's magnet, for instance, costs something like £2 an hour in electricity and a few shillings an hour in water (6,000 gallons per hour), when running at full power. They have, however, many technical advantages apart from their cheap initial cost, which outweigh the high running cost, and they are likely to be used more and more in the future.

A less obvious but very ingenious way of avoiding the heating difficulty was used by the Russian scientist, Peter Kapitza. For many purposes a magnetic field lasting for only a very short time is quite adequate, and this can be achieved by momentarily passing a large current through a solenoid. This not only avoids excessive heating, but enables much larger powers to be drawn from the electric source than would be possible in steady conditions. The basic principle is to provide a large store of electric energy and then to discharge it rapidly through the solenoid. Several means of storing large electric energies are possible, as for instance in a large bank of electric condensers, or in a large accumulator battery, or in a dynamo, but in each case elaborate and expensive equipment is necessary, and complicated switching mechanisms are required to ensure that the discharge is limited. Kapitza first tried the accumulator method, but later found the dynamo method more reliable; with recent advances in condenser design it is possible that the condenser method might prove even better. The dynamo equipment (see plate IV) was set up in Cambridge in 1926, first in a large shed and later in the Royal Society Mond Laboratory (built specially to house it); it has since gone to Kapitza's Moscow laboratory where it is still working well.

The dynamo is connected to the solenoid only during a single half cycle of its rotation (about 0·01 second), and during this time the current rises to about 15,000 amps. and then falls again to zero. The biggest magnetic field Kapitza has produced in this way is about 300,000 gauss, though with more elaborate equipment even a million gauss should be attainable. An important limitation which makes it very difficult to reach higher fields is the enormous mechanical stress (proportional to the square of the field) to which the solenoid coil is subjected during the current discharge. In the early experiments the coil occasionally burst, and special reinforcement had to be designed before it would stand up to the stress safely.

Although the field lasts for only 0·01 second it is quite possible to carry out magnetic measurements in this time, using specially designed automatic recording devices. Kapitza is rather proud of this and likes to tell visitors that he is the highest paid scientist in the world, receiving a professor's salary for experiments which last only a few seconds in a year! Another interesting feature of his method is that the laboratory undergoes a minor earthquake when the current is discharged, because of the sudden reduction of the rotational speed of the dynamo (it is the rotational energy, of course, which is converted into electric power). To avoid upsetting the delicate recording instruments, Kapitza placed them at such a distance from the dynamo that the shock wave (which travels with the speed of sound in the floor of the building) reaches them only after the recording is complete. It was this feature which determined the rather attractive design of the Royal Society Mond Laboratory, whose main hall had to accommodate the equipment (see plate IV). The length of the hall was made just long enough (about 90 feet) so that the proper distance separated the dynamo and the recording instruments

(placed close to the solenoid), and this hall now provides a pleasant promenade for research workers in the adjoining rooms.

We have left to the last the best known type of electromagnet, which, though very useful for most laboratory work, cannot give such high fields as Kapitza's impulsive method or Bitter's water-cooled coil. This type is based on the use of a coil with an iron core. The iron core is usually shaped in much the same way as the body of a horse-shoe permanent magnet, but the material used is soft iron with little hysteresis and high permeability. When current flows through coils wound on this core, the iron becomes magnetized and a field is produced in the gap in much the same way as with a permanent magnet, except that here the magnetism is not permanent, but requires the magnetizing field of the coils. Just as the field of a permanent magnet is limited by the remanence and coercivity of the permanent magnet steel, so here the limit is set by the saturation magnetization of the iron, and it is difficult to obtain fields very much larger than the magnetic induction of the saturated iron, which is about 20,000 gauss, plus the magnetizing field of the coils acting alone.

Some increase can be obtained by tapering the iron core at its ends, for the field is then enhanced by the poles on the sloping parts of the tapered ends, but the increase is small unless the whole size of the magnet is made very great compared to the gap dimensions. By using large currents in the magnetizing coils (with water cooling to remove the heat) the extra contribution of the coils themselves can be made quite large, but in this case we owe the large field rather to the ordinary solenoid principle than to the iron core. The real benefit of the iron core is for low currents, where considerable magnetization of the iron and a fairly large field in the gap are obtained with a low expenditure

of electric power on account of the high permeability of soft iron.

Some typical electromagnets of the iron cored variety are shown in plates V and VII to illustrate the wide range of sizes used in different laboratories. Plate VII*b* shows a small electromagnet, used for teaching purposes, in the Cavendish laboratory; it produces a field of order 10,000 gauss in a volume of about 1 cc. with a current of only 1½ amps., which involves a power of only 300 watts and requires no water cooling. Next comes a larger magnet (plate V*a*), used in the Royal Society Mond Laboratory, of a type designed by Weiss; here the coils are wound with copper tubing through which cooling water is circulated. As in all such magnets the field obtained depends on the shape of the *pole pieces* as the terminations of the iron core are called and on the size of the gap, and these pole pieces are made detachable so that a variety of conditions can be achieved. With flat-ended pole pieces separated by a gap of an inch or so a field of 20,000 gauss can be obtained over a volume of several hundred cc., using a current of 60 amps. (a power of about 6 kW.), while with coned pole pieces, tapered down to only a cm. diameter, and with a small gap, fields as high as 40,000 gauss are obtainable over a volume of about 1 cc.

Until fairly recently the largest magnet in the world of this kind was the 110-ton Bellevue magnet built in 1928 by Cotton and shown in plate VII*a*. In ordinary use, the fields obtainable are not very much larger than those of the Weiss magnet but they can be obtained over much larger volumes and of course more power (about 100 kW.) is required. For instance, a field of 40,000 gauss is obtainable over about 20 cc., and a field of 20,000 gauss over about 50 litres (i.e. 50,000 cc.). With the help of auxiliary water-cooled coils (not illustrated) over the pole pieces and with the expenditure of about

1,000 kW. of power, a field of 100,000 gauss can be produced in a volume of 1 cc. However, as we have already explained (p. 161), a large part of this field is contributed by the solenoid principle rather than by the iron core, and the same result can now be obtained with much smaller capital outlay in Bitter's solenoid which does not use any iron at all.

The world's record for size in electromagnets has recently been beaten by the Berkeley (U.S.A.) *synchro-cyclotron* magnet, also illustrated on Plate VII. Here the aim is not so much to produce a very high field (only some 14,000 gauss is required), but to produce it over an enormous volume. The diameter of the pole faces is 184 inches and the whole magnet weighs 4,000 tons—its enormous size can be judged from the illustration which shows a man standing beside it. An explanation of how the magnetic field is used is given on p. 175.

2. *Bending of beams of charged particles by magnetic fields*

The principle of the electric motor—the force exerted by a magnetic field on a current of electricity—is of immense importance for scientific applications, for it implies that a beam of electrically charged particles travelling in a straight line (which behaves like a current) can be deflected by a magnetic field. This deflection has been used in a great variety of ways and has been fundamental in the rapid development of atomic and nuclear physics, both in elucidating the nature of different kinds of charged particles and, less directly, in providing such atom-splitting machines as the cyclotron and the betatron. The same principle is basic also in the magnetron valve which made possible the production of the intense ultra short radio waves used in centimetric radar.

Let us see how the principle works. Suppose we

have a beam of particles of charge e and mass m, travelling along with velocity v. Such a beam is equivalent to an electric current, and if a magnetic field H is applied in a direction perpendicular to the line of travel, a force acts on each particle perpendicular both to H and to the line of travel. This has the effect of bending the beam into a circular path round the magnetic field direction and it is an easy matter to calculate the radius of this circular path. In fact, the radius of the circle is such that the centrifugal force acting on the particle (because of its curved path) is just equal to the magnetic force deflecting it. The centrifugal force is mv^2/r and the magnetic force is Hev, so we have that

$$r = mv/He$$

This means that the circular path has least radius for light particles of big charge moving slowly, and for high fields. For instance, an electron is much more easily bent into a circle than a *proton* (which is the nucleus of a hydrogen atom and is nearly 2,000 times heavier than an electron), and a slow electron is more easily bent than a fast one. To see whether the principle is of any practical use we must put in some numerical values, for, unless the radius comes out to be reasonably small, the magnetic deflection will be too small to be observed. A typical electron speed is 10^{10} cm./second (about 60,000 miles per second) and the ratio e/m for an electron is $1{\cdot}8 \times 10^7$, so for a field H of 1,000 gauss (which as we have seen is easily obtained by laboratory magnets), we find $r = 0{\cdot}6$ cm., which is quite small enough to be easily observed.

For a proton of the same speed the radius would be about 2,000 times greater, or about 1,200 cm., and the deflection would be very slight (though just detectable with careful measurement), but by using a field twenty times larger it would become 60 cm., which is more easily detectable. Of course, with such a large radius

only part of the full circle would be described unless the magnet was large enough to have a uniform field over the whole area of the circle, for it is only while travelling through the field that the path is circular.

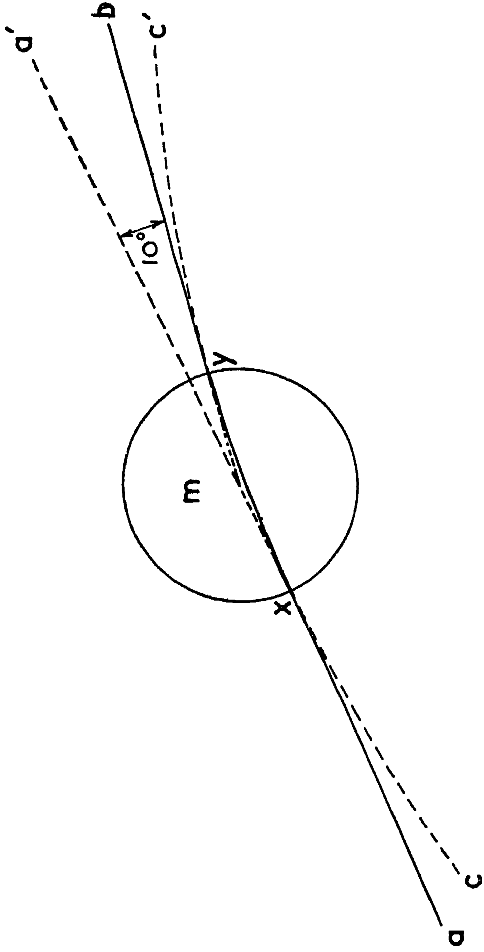

Fig. 51.—Deviation of a proton in passing through a magnetic field of 20,000 gauss. The proton is originally travelling along the straight line *axa'*; when it passes between the poles *m* of the magnet it is bent into the path *xy* (part of the circle *cc'*) and on leaving the magnet travels again along a straight line (*yb*), but at an angle to its original direction. The radius of curvature of *cc'* is about 60 cm., so if *m* has a diameter of 10 cm., the deviation angle is approximately 10/60 radians, or about 10°, as shown.

Once the beam has left the field it straightens out again, but we can measure the radius of the circular arc by observing the deflection of the beam direction. This is illustrated in fig. 51, which shows the path of a proton beam in a small magnet of diameter 10 cm.

The first use of this principle was made by J. J. Thomson in proving the existence of electrons. He found that the so-called *cathode rays* produced in an evacuated electrical discharge tube could be deflected by a magnetic field and he suggested that the rays were a beam of charged particles.* The direction of the deflection showed that they were negatively charged particles, and he set about measuring the ratio e/m for these particles. Since the velocity of the particles was unknown, this ratio could not be deduced from the magnetic deflection alone; the beam could, however, also be deflected by an electric field (as is to be expected for charged particles), and this enabled the problem to be solved. An electric field E also exerts a force on the particles given by eE, and by opposing the electric and magnetic forces, Thomson was able to balance them so that the beam was undeflected.

Evidently this balance will require that

$$eE = Hev$$

so the velocity is given by E/H when the fields have been adjusted for balance. Once the velocity is known, e/m can be deduced from the magnetic deflection acting alone. Thomson found that e/m always had the same value (about $1{\cdot}8 \times 10^7$) whatever the condition of the discharge tube. Soon afterwards exactly the same ratio turned up with beams of particles from a surface illuminated by light or X-rays (*photoelectric effect*), from heated metals in an evacuated vessel (this is the *thermionic effect* which is the basis of radio valves),

* These rays make possible many modern devices such as the cathode ray oscillograph (used extensively in radar) and television. For further details see *Electrons in Action* by J. G. Daunt.

and for the *β-rays* emitted by radioactive particles. Evidently in all these cases the particles are identical and they seem to be a fundamental brick in the structure of matter. They were called *electrons*, and we have already outlined (Chapter 4) how they enter into the architecture of the atom.

The same kind of method was later used by Thomson in studying the ratio of charge to mass of charged atoms, and led to the discovery of *isotopes*. It was found that some atoms could exist in several variants of slightly different masses, but all having the same number of electrons (same atomic number) and hence the same chemical behaviour ; such variants of the same atomic number but different mass are called isotopes. For instance, neon, which has an atomic weight 20·18, turned out to be composed mostly of atoms of mass 20, but partly also of atoms of mass 22. This discovery was followed up by Aston, who constructed an elaborate machine called a *mass spectrograph* which enabled him not only to discover the existence of many new isotopes, but to measure their masses very accurately. He found that the masses of atoms, though always nearly integers (on the scale which makes hydrogen unity), were not exactly integers, and accurate knowledge of the small differences has been of immense value in unravelling the structure of the atomic nucleus, the core of the atom which carries nearly all the mass.

In Aston's mass spectograph the different kinds of atoms, ionized to give them one or two electrons of positive charge, are first made to have the same velocity, and then are sorted out according to their masses by their different magnetic deflections. Only minute quantities of matter are sorted out in this way however ; in fact only enough to make traces on a photographic plate. The same principle, can, however, be used to separate appreciable quantities of different isotopes. This was first achieved in the Cavendish Laboratory

when Crowther and Shire separated the two isotopes of lithium in sufficient quantities to make experiments with the separate species, but even then the quantities were still minute, measured in fractions of micrograms. The great technical difficulty in such separations is to provide powerful enough sources of the charged atoms (or *ions* as they are called). Very recently this technical difficulty has been overcome by various ingenious methods which cannot be explained here, and the most spectacular triumph of the method has been the separation of really large quantities—measured in pounds rather than micrograms—of the uranium isotopes. To make an atomic bomb many pounds of the uranium isotope of mass 235 are required, but ordinary uranium consists mainly of the 238 isotope, with an admixture of less than 1 per cent. of the 235 isotope. All sorts of separation methods were tried, and one of the most successful was the one just outlined.

The practical realization of this scheme was not only a matter of overcoming the technical difficulties just outlined, but also of building very large-scale plant involving millions of dollars expenditure. Details of the Oak Ridge plant where this was achieved are still secret, but it is known that hundreds of large magnets are used, each sorting out the two isotopes by their different magnetic deflections. The magnets have to be very large, not so much because large fields are required (15,000 gauss is sufficient), but because the field is required over a large area, large enough to produce an appreciable separation of the 235 and 238 beams. Since each ion is much heavier than a proton, we can see from our previous calculation that the magnetic deflections are very small and only very slightly different unless the ion beams have a very long path in the magnetic field.

An interesting sidelight on magnet design is provided

by the Oak Ridge plant. We have mentioned that the power consumption of an electromagnet is slightly less for silver than for copper coils; ordinarily the economy involved (about 6 per cent.) would not justify the much higher cost of silver, but in a scheme of this magnitude, where the power consumption is comparable to that of the whole of London, the saving is important. It so happened that a great deal of silver was available in the American banks, and the American Government decided that 14,000 tons of silver would be better used for saving power in the Oak Ridge plant than lying idle in the bank vaults. It is a pity that it is only for war purposes that bankers can become so broad-minded.

Another important use of the magnetic deflection principle is to measure the velocities of particles whose e/m is known. This, too, has been of great value in various problems of atomic physics. For instance, if a beam of β-rays is emitted by a radioactive substance between the pole faces of a large magnet, particles of various speeds are bent into circles of various radii. If a photographic plate is put diametrically opposite to the source it receives the different beams at different points on its surface (fig. 52) and we get a kind of *velocity spectrum*: each point on the plate corresponds to a definite velocity and from the observed blackening of the plate when developed we can deduce the proportions of particles which have the various velocities. With the help of such a *magnetic spectrograph*, Ellis made a detailed study of this velocity spectrum for different kinds of β-rays and the information he obtained led to important conclusions about what was going on in the nuclei of the radioactive atoms.

The same idea has been used in the study of *cosmic rays*—the mysterious radiation which reaches the earth continuously from outer space. By means of an ingenious apparatus known as the *Wilson cloud*

chamber, the tracks of particles such as electrons and charged atoms can be photographed. If the Wilson chamber is placed in a magnetic field the tracks become curved, and so the velocities can be deduced if the type

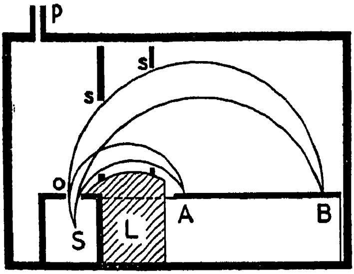

Fig. 52.—A β-ray spectrograph. The whole box is placed in a magnetic field perpendicular to the paper and is evacuated by a pump connected to p in order that the β-rays should not be scattered by gas molecules in the box. S is a radioactive source emitting β-rays, which pass through the slit o and the wider slits s. All rays of the same velocity are bent into circles to reach the photographic plate AB at nearly the same point ; B represents the point for a high velocity and A for a low velocity. The plate is blackened according to the intensity of the β-rays falling on it and so a velocity spectrum is produced on the plate. L is a block of lead to shield the plate from stray radiation.

of particle (and so its e/m) is known. The nature of the particle can usually be deduced from the appearance of the track, and in cosmic rays it is usually electrons that are observed. Blackett, in Cambridge, and Anderson, in California, found, however, that some of their tracks which looked exactly like electron

tracks, curved the wrong way, and this suggested that the particles concerned were positively instead of negatively charged, though otherwise just like electrons. These new particles are called *positrons* and their discovery has been very important in the development of nuclear physics. More recently another new kind of particle, the *meson*, with a mass about 200 times that of the electron has been discovered.

The energy spectrum of particles in cosmic rays reaches out to fantastically high energies. Actually our theory of the magnetic deflection has to be modified when the velocity is too high; relativity takes control and does not allow the velocity to exceed the velocity of light (3×10^{10} cm./sec.), but the mass increases as the energy goes up, so that the magnetic deflection gets smaller and smaller even though the velocity never passes this limit. Practical possibilities set a limit to the energies that can be measured by magnetic deflection since, if the energy is too high, the curvature becomes too small to be measured, but particles are found in cosmic rays with energies right up to this practical limit, and probably still higher energies occur too. An interesting result that comes out of such measurements is that the most energetic particles observed have an energy greater than could be obtained if all the mass of the heaviest atomic nucleus was destroyed and converted into energy. How so much energy is produced is, in fact, one of the great mysteries of modern physics and the solution of this puzzle may lead to exciting new discoveries.

The magnetic deflection method is used in yet another way in studying the cosmic rays. The earth is, as we have seen, a large magnet, and in a sense it acts as if it were itself a large magnetic spectrograph. Charged particles coming in from outer space are deflected by the earth's magnetic field, but their path is more complicated than in an ordinary magnetic spectro-

graph, since the earth's field is not uniform and not always perpendicular to the track of the particles. Rather elaborate calculations show that above a certain magnetic latitude incoming particles of all energies but the very slowest can reach the earth, but below this latitude only the most energetic ones arrive, while the paths of the slower ones miss the earth altogether. So, by measuring the intensity of cosmic rays at different latitudes much can be learnt about the energy spectrum of the cosmic ray particles, and the fact that a latitude effect occurs at all, confirms that the particles arrive from far outside the earth's atmosphere.

3. *Splitting the atom with the help of magnetism: the cyclotron and betatron*

The problem of splitting the atomic nucleus is basically one of producing sufficiently energetic particles to act as bombarding bullets. In many cases the bombarding particle (usually itself an atomic nucleus) has to have an energy equivalent to that which it would acquire if it were accelerated by a potential drop of several million volts. Such high potential differences can indeed be produced by direct means, but apparatus of enormous dimensions is required, and, in 1932, Lawrence in Berkeley, California, invented a new method of acceleration which he called the *cyclotron*. The basic principle of this is again the fact that a charged particle moves in a circular path between the poles of a magnet. If we look again at our formula (p. 164) for the radius r, of the circle, we can calculate the time taken to travel once round the circle; this time is just $2\pi r/v$ and so, using our formula we find the time is $2\pi m/He$. It is this result which makes the cyclotron possible, for it shows that the time of revolution is independent of the radius of the circle and the velocity of the moving particle.

The particle is made to travel within a split metal

box of the shape shown in fig. 53, placed between the pole pieces of a large electromagnet. Between the two halves of the box (called D's because of their shape) a rapidly alternating electric potential is

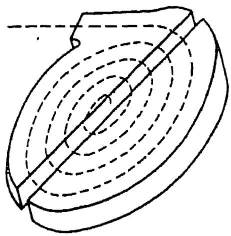

Fig. 53.—The principle of a cyclotron. Positively charged ions emitted at the centre of the apparatus are bent into circles by a magnetic field applied perpendicular to the shallow D's (seen in perspective here). Each time the circular path crosses the gap between the D's the ions are accelerated by a high frequency electric field between the D's, which is synchronized to act in the right direction each time. The path thus becomes a spiral and eventually the ion passes out of the D's with a very high velocity.

applied; if the frequency of this potential is chosen correctly, the particle in its circular path crosses the gap always just at the moment when the potential acts to accelerate it. After this acceleration the particle moves in a slightly larger circle, but the time taken to get round the next half circle is unchanged and the potential has then just reversed, so that it again accelerates the particle across the gap. This process goes on driving the particle round a spiral until the radius becomes nearly that of the box. At this stage, the particle has the same energy as if it had been

accelerated by a potential equal to the gap potential multiplied by the number of times it has crossed the gap, and thus can fairly easily be made millions of volts. The process is stopped by a deflecting electric field near the circumference of the box, which draws the particles to one side and enables them to leave the box and be used to bombard other atoms.

The whole process depends, as we have said, on the constancy of the time of rotation of the particle so that the alternating electric potential can keep in step with the rotation, and we must see that the time involved is a reasonable one. Putting in numerical values for a *deuteron*, which is the nucleus of a heavy isotope of hydrogen ($e/m = 5 \times 10^3$, roughly), and taking $H =$ 15,000 gauss (about as high as is practicable over the large space required), we find that the time is $2\pi/15{,}000 \times 5 \times 10^3$, or roughly 10^{-7} seconds. The potential across the gap must, therefore, alternate with a frequency of 10^7 cycles/sec. to keep pace with the rotation, and fortunately this is technically feasible, for this frequency is just that of a short-wave 30 metres wave-length) wireless transmitter.

The cyclotron seems at first sight to have almost unlimited possibilities, for by making the magnet large enough it seems that the particles could be accelerated to almost any energy we please. In fact our formula shows that for a given magnetic field the radius of the magnet pole pieces must be increased in proportion to the velocity which is to be achieved, or to the square root of the energy (which is $\frac{1}{2}mv^2$). Lawrence's first cyclotron was quite a modest affair, with magnet pole pieces only a foot or two in diameter and yielding only a few million volts of acceleration for deuterons, but, since then, bigger and bigger ones have been built, particularly in the U.S.A., and Lawrence has just constructed one with pole pieces nearly sixteen feet across, designed to give more than

a hundred million volts acceleration. A general view of this huge machine is shown in plate VII; a description of the magnet has already been given on p. 163.

Such increases are not merely a matter of finding the right number of *megabucks* (a convenient unit of a million dollars for measuring the cost of such machines) to pay for the equipment—and this is no trifling matter, for the cost goes up roughly as the cube of the magnet pole face diameter—but serious difficulties of principle have to be overcome. If the accelerated particles move too fast, relativity effects begin to become important; the mass begins to increase and so the time of rotation can no longer keep quite in step with the constant frequency of the accelerating potential.

Various ingenious methods have been suggested for dealing with this difficulty; in the new cyclotron just mentioned, the difficulty is overcome by varying the frequency to follow synchronously the acceleration of a "bunch" of particles emitted at one particular instant. This process is repeated many times a second and at the end of each cycle of frequency change a "bunch" of fully accelerated particles leaves the cyclotron. To distinguish it from other cyclotrons, this particular type is called a *synchro-cyclotron* or sometimes a *frequency modulated cyclotron*.

In the cyclotron it is only heavy particles, such as deuterons or protons, rather than electrons, which are accelerated; this is because the difficulty, just mentioned, of the mass increasing with velocity, sets in much earlier with a light particle such as an electron than it does with a heavy one. Recently a rather different machine for accelerating electrons has been successfully developed by Kerst at the General Electric Company of America. This is the *betatron* (see plate VIII) and, although it too depends on bending the electrons into a circular path by a magnetic field, it uses an entirely different principle to accelerate the electrons. This

new principle is none other than Faraday's law of induction. We saw in Chapter 2 that when the magnetic field changes it produces an electric field whose lines of force go in circles round the changing magnetic field. This electric field can be used to accelerate electrons which follow a circular path because they are already in the magnetic field.

The working out of the principle is very complicated, but essentially the betatron consists of a magnet whose field is rapidly increased and decreased by feeding it with alternating current; the magnet core has to be laminated to reduce the eddy currents, which would otherwise seriously limit the fields attainable. During the increase of field, electrons emitted at the centre of the field in the proper direction are accelerated by the Faraday electric field, and revolve many times in a spiral path which brings them to the periphery of the magnet just when the field has reached its peak value. By this time they have enormous energies—in Kerst's betatron as high as if they had been accelerated by 100 million volts (the energy depends just as before on the size of the magnet), and they can be used to produce effects in the laboratory which hitherto were possible only with cosmic ray particles. It will be noticed that the acceleration is produced only during the increasing part of a cycle, and so, just as in the synchro-cyclotron, the high energy particles are produced in a series of bursts, one burst per cycle.

4. *The magnetron*

A full account of this device would require too much introduction about the technique of generating short wireless waves, but we can indicate the basic principle quite briefly without filling in the gaps. We have seen that the time of rotation of a charged particle in a magnetic field is given by $2\pi m/He$. For electrons in a field of 1,000 gauss this gives a time of $3{\cdot}5\times10^{-10}$

seconds, or a frequency of rotation of 3×10^9 per second. In the *magnetron* (see plate VIII) electrons are emitted by a heated filament in an evacuated tube which is placed in a suitable magnetic field and the electron rotations are able to produce a periodic disturbance, or oscillation, in a circuit coupled to the magnetron, with just the same frequency as the electron rotation itself. This oscillation, if applied to a suitable aerial, makes it emit wireless waves of about 10 cm. wave-length. If the field is increased to 3,000 gauss, the frequency is 3 times higher and the wave-length is about 3 cm. Now it is just such short wave-lengths which are most useful for radar, among other reasons because the size of the whole equipment and its aerial is determined mainly by the wave-length and this has to be kept small in an equipment which is to go in an aircraft. The magnetron proved of immense value in the war, for, although it is not the only method of producing such short waves, it can produce much more powerful pulses of waves than any other method, and this is very important in extending the range over which radar works.

5. *The production of super-low temperatures by magnetic means*

We now turn to a magnetic tool of quite a different kind, depending for its working not just on the general laws of electro-magnetism, as have all the previous ones, but on the magnetic properties of matter, and in particular of paramagnetic salts. This is the *adiabatic demagnetization* method for reaching temperatures very close to the absolute zero. The method was proposed in 1926 independently by Debye, in Germany, and Giauque, in California, entirely on theoretical grounds, and it has since been proved in practice in most of the world's low temperature laboratories, so that temperatures of one-thousandth of a degree absolute are now almost a commonplace.

If a paramagnetic salt is magnetized by a strong magnetic field, a small amount of heat is evolved. As we saw in Chapter 4, the magnetic moments of its atoms become slightly more ordered and tend to line up with the field direction. Now, it is known from thermodynamics that there is a fundamental connection between the degree of order of a substance and the amount of heat it contains, so that if the degree of order is increased heat must be evolved. Conversely, if the magnetic field is removed, the substance tries to absorb heat from its surroundings to balance the decrease in its degree of order, and if it is isolated from its surroundings it cools down. The amount of ordering produced by a magnetic field gets larger as the temperature is reduced, because the thermal agitation of the atoms is then less effective in hindering the ordering process, so these cooling and heating effects are much more marked at low temperatures. The lowest temperature that can be conveniently reached in the laboratory, by other means than the adiabatic demagnetization process, is about 1 °K., which is that of liquid helium boiling at as low a pressure as can be reached by large capacity pumps connected to the vessel in which it boils. If this low temperature is used as a starting point, much lower temperatures can be reached by the demagnetization process.

The practical realization of the principle is illustrated schematically in fig. 54, and a photograph of an actual apparatus appears in plate V. The salt is contained in an inner tube which can be thermally isolated from the surrounding liquid helium bath by pumping away all the gas in the tube, or thermally connected by letting gas in. The liquid helium is contained in a Dewar vessel (a kind of " Thermos " flask) and is surrounded by another Dewar vessel containing liquid nitrogen or liquid air (to reduce the heat inflow into the liquid helium,

which would otherwise boil too rapidly). The whole apparatus is mounted in a magnet—either in a water-cooled solenoid of the Bitter type, or between the poles of an ordinary electromagnet. At the start of the process gas is kept in the inner tube so that the salt cools down to the bath temperature (about 1°K.). When the

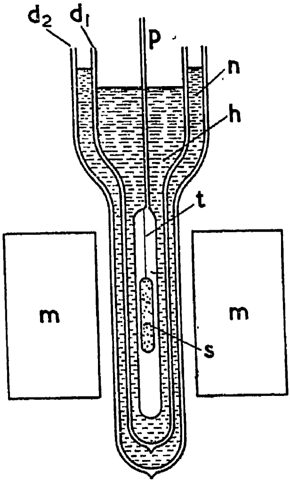

Fig. 54.—Schematic diagram of an apparatus to produce magnetic cooling. The magnet *m* is a water-cooled coil; the salt *s* is suspended by a thread *t* inside a tube which can be evacuated through *p*. Around the tube is liquid helium *h* in a Dewar vessel d_1, surrounded in turn by liquid nitrogen, *n*, in a second Dewar vessel d_2. The salt attains the temperature of the liquid helium by conduction of heat through the gas, but when the gas is pumped off, *s* is thermally isolated, and if the magnet is switched off *s* cools down to very low temperatures. A photograph of an actual apparatus is shown in plate V.

magnetic field (30,000 gauss is a suitable field), is switched on, heat is evolved, but this is communicated to the bath and merely boils away a little of the liquid helium. In a few seconds thermal equilibrium is restored and the salt is again at 1°, but now in a magnetic field. Next the gas is pumped away from the inner tube, so that the salt is thermally isolated, and then the magnetic field is switched off. During this *adiabatic demagnetization* ("adiabatic" means thermally isolated) the salt cools down to a very low temperature, a few thousandths of a degree or so, depending on the detailed conditions.

This low temperature can be demonstrated by measuring the magnetic susceptibility of the salt, for we have seen that according to Curie's law the susceptibility is inversely proportional to the absolute temperature, and this susceptibility is indeed found to have increased several hundred times over its value at 1°K., showing that the temperature has decreased by the same factor. In all this description we have tacitly assumed that our paramagnetic salt has "ideal" properties with neglible interactions between its magnetic carriers. Actually it can be shown that if this were so the salt would cool down to the absolute zero, and it is the existence of slight interactions which limits the temperature attainable. The smaller are these interactions, the lower is the temperature which can be reached, and so careful choice of the salt is essential to obtain the best results. As we mentioned in Chapter 4 (p. 94) particularly small interaction effects are obtained with salts in which the magnetic carriers are electron spins with no contribution from the electron orbits, and in which the magnetic carriers are diluted by non-magnetic atoms or ions. It is, indeed, found that salts of this kind (of which potassium-chrome alum is an example) are the most effective, but the theory of the slight interactions which still

remain and which determine the lowest temperature attainable, is complicated and experiment provides the best guide in the choice of salt.

What is the use of such super-low temperatures? If it were only a question of breaking records the method would have little more than sporting interest, but actually there is considerable scientific interest in studying the properties of matter at such low temperatures, and the method is likely to be important in the future. It has already yielded results of considerable importance for understanding the detailed behaviour of the paramagnetic salt which is cooled down (see p. 102), but its interest for the future is more in using it to cool down other substances—technically a difficult problem but one that is now actively being attacked. There is also the possibility of using the low temperatures as a starting point for demagnetizing the magnetism due to the magnetic moments of atomic nuclei. This magnetism is negligible at ordinary temperatures, because nuclear magnetic moments are about 2,000 times feebler than atomic moments, but should be sufficient at 0·001 °K. to start a demagnetization process reaching down to perhaps a millionth of a degree, limited again by the feeble interactions between the nuclear moments.

6. *Applications to chemistry and biology*

The chemist's interest in magnetism is mainly concerned with its bearing on the structure of organic molecules—the rich variety of combinations of carbon, hydrogen, oxygen and other atoms which go to make up substances produced by living organisms. Pascal (not the famous philosopher, but a contemporary French magnetician) made an extensive study of the magnetic susceptibilities of organic substances and found that they obeyed relatively simple laws. The susceptibilities were usually feeble and diamagnetic and Pascal showed

that they could be built up by adding the susceptibilities of the constituent atoms, together with a constant which was characteristic of the kind of bonds linking the atoms together. The nature of these bonds is very important for the chemist, and the evidence about them revealed by Pascal's work, and later that of Bhatnagar in India and others, has often proved a useful guide when other evidence was inconclusive.

Another link with chemistry has been the study of the magnetic properties of single crystals of chemical substances (particularly organic compounds). From the variation of susceptibility with the direction of the magnetic field relative to the crystal axes, K. S. Krishnan has been able to deduce useful information about the shape of the molecules of the crystal and the nature of the complicated electron orbits round the various atoms of which the molecule is made up.

Up to now biologists have been only rather indirectly concerned with magnetism. As mentioned in Chapter 1, no direct effects of a magnetic field on living organism have yet been found; mice and guinea-pigs kept in magnetic fields of tens of thousands of gauss for many days do not appear to be affected to any appreciable extent. This is not, perhaps, very surprising, for since organic substances of which living bodies are built are only very feebly magnetic, the changes produced in the electronic motions within their molecules, even by the largest laboratory fields, are very slight indeed. The less direct biological interest in magnetism is mainly very similar to the chemical one. The magnetic susceptibility sometimes provides a convenient index to subtle chemical changes which happen in biological processes, and which are difficult to follow by other methods.

Sometimes also, magnetic techniques may be useful in solving special biological problems. An example of this was the study of the mechanism which enabled a

crayfish to swim the right way up. It was suspected that this mechanism was connected with the action of gravity on fluids in the crayfish's semicircular canal, and it was possible to demonstrate this by filling the canal with iron filings and letting the crayfish swim in a strong inhomogeneous magnetic field. The magnetic force on the iron filings could be made stronger than the force of gravity and it was found that when the resultant force acted upwards the crayfish swam upside-down. As far as the crayfish was concerned, gravity seemed to have reversed its direction and the crayfish reacted accordingly.

Chapter Eight

MAGNETISM IN EVERYDAY LIFE

1. *Introduction*

WE have seen in the last chapter that magnetic principles and magnetic devices are very important in the scientific laboratory, and we shall now show how they are used in many phases of everyday life—in technical and industrial applications which make modern civilization possible. Some of the most important applications have already been mentioned as examples of the fundamental principles on which they are based. The dynamo which generates electric current, the electric motor driven by the force between a magnet and an electric current, the transformer which is essential in the widespread distribution of electric power and the use of magnets in electrical measuring instruments, have all been dealt with in previous chapters. In this chapter we shall describe a few other practical uses of magnetism which are of general interest. Nearly all the examples we shall deal with are based on the strong magnetic properties of iron, and they can be broadly classified into applications which make use of the earth's magnetic field and those which merely rely on the attraction of iron to a magnet.

2. *Detection of minerals and other buried objects*

The most important use of the earth's magnetic field is the mariners' compass, but we have said enough about this in Chapter 6, and here we shall describe only the less obvious applications—the magnetic detection

of minerals and buried metals, the magnetic mine and the measures used to counter it.

It was mentioned in Chapter 6 that the earth's magnetic field often displays local irregularities due to the presence of iron ores close to the surface. A careful survey of the earth's field can therefore be used to reveal the presence of such buried ores, and has in fact proved very useful for prospecting. At first sight, it might seem that it was only for iron ore prospecting that such a method could be used, since other valuable minerals such as gold and oil are practically non-magnetic and their presence could hardly affect the earth's magnetic field. They do, however, often have an indirect effect which can be used to locate them. Thus, oil is often found trapped in a kind of hollow bump or dome under the earth, of the kind shown in fig. 55, and under it there is a corresponding bump in the rock layer. Now this rock layer contains more iron than the upper layers, so the bump causes a local increase of the earth's magnetic field just above the oil dome and the oil can be detected by a careful magnetic survey of the surface above it. Similarly many of the gold deposits in South Africa are associated with magnetic deposits, so once again their course can be followed by following the field irregularities caused by the iron. The modern method of survey is from an aeroplane towing what the Americans call a " doodle-bug " containing suitable apparatus connected to the recording apparatus in the aircraft. In this way large areas can be covered much more rapidly than by the older method of surveying on the ground. This principle of " doodle-bugging " was used considerably during the war for locating submarines instead of oil: a submarine is built largely of iron and so it, too, causes a local irregularity of magnetic field around it, sufficient to be detected by an aeroplane flying low over the sea.

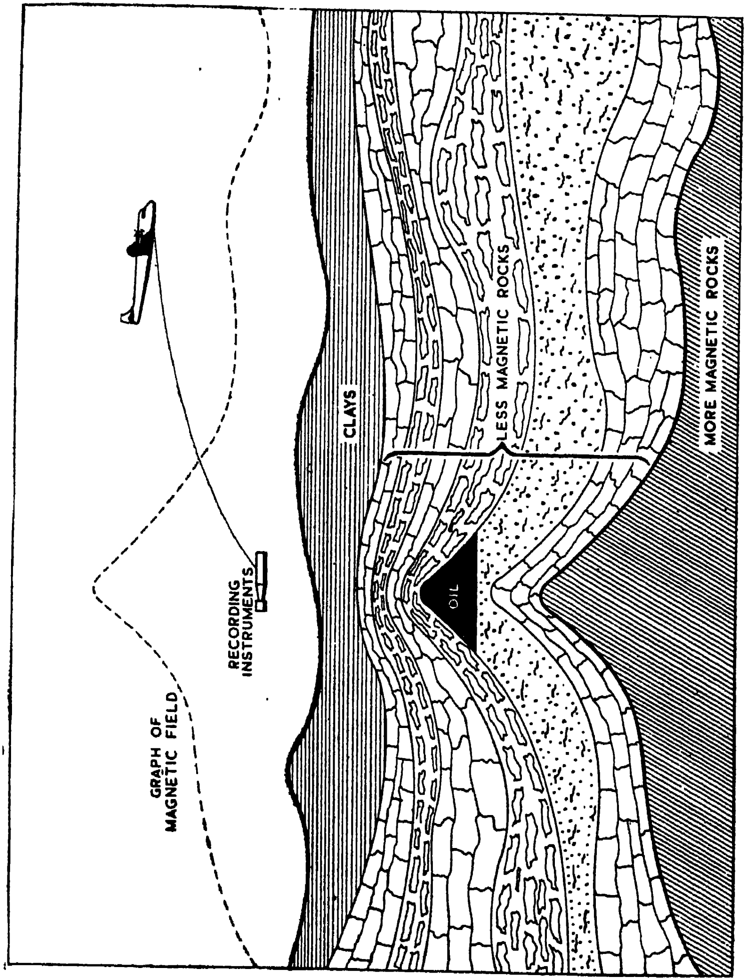

Fig. 55.—Prospecting for oil by aeroplane. The presence of oil is suggested by a maximum of magnetic field recorded when the aeroplane flies over the hump in the layer of magnetic rocks, associated with the oil-containing dome.

Another war-time use of the same principle was the detection of buried land mines, and the location of unexploded bombs, so that they could be dug out as

quickly as possible and rendered harmless. Here the amount of iron is much smaller than that in a submarine, but the depth below the surface is much smaller. If a suitable apparatus which responds to slight changes of magnetic field is carried over the mine or bomb it will respond to the slight field irregularity caused by the object and thus reveal its location. The apparatus has to have great sensitivity, since the iron object is only feebly magnetized by the earth's field and the extra field produced by this magnetization falls off as the cube of the distance. In practice, it is difficult to detect an iron object at a distance of more than three or four times the size of the object; thus a landmine, or a small bomb, cannot easily be detected more than a few feet away.

It will be noticed that this kind of method depends entirely on the object being made of a ferromagnetic material, and an alternative method was developed which would detect any metal object, even if it is not iron. This was based on the eddy currents induced in any mass of metal (even if it is non-magnetic) by an alternating magnetic field. The magnetic field of the eddy currents reacts back on the source of the alternating field—usually a large loop of metal tube, fed with alternating current of fairly high frequency—and this reaction, after passing through various circuits, shows itself either by a change in a buzzing note or by a lamp lighting up. This alternative method has in principle rather a shorter range, since the strength of the induced eddy currents decreases roughly as the cube of the distance away from the loop, and the effect of the eddy currents at the loop again decreases as the cube of the distance, so that in all, the effect falls off something like the sixth power of the distance. In practice a land mine cannot be detected at much more than two feet in this way, but the eddy current

method has the great practical advantage that it does not depend on the earth's magnetic field and so is not subject to certain difficulties associated with the other method.

We have talked rather vaguely of detecting irregularities of the earth's magnet field by suitable instruments and we must now say a little about the instruments that are used. In principle an ordinary compass needle would show up such irregularities, but in practice it is usually too insensitive, unless it is made very complicated. Usually electrical methods are used, and often of a very indirect kind; we shall describe only one of these methods which provides an interesting illustration of several different magnetic principles.

Certain alloys of iron and nickel have very striking magnetic properties; we have already mentioned in Chapter 5 permalloy, with its enormous initial permeability, and another one is *mu-metal*, which also has very high permeability, but a permeability that varies strongly in small magnetic fields. If, then, a mu-metal wire is placed in the earth's magnetic field, its permeability will depend on the strength of the field and small changes of the field will cause considerable changes of permeability. When alternating current is passed through the wire it tends to flow more on the surface of the wire than in the interior, and the extent of this *skin effect*, as it is called, depends strongly on the permeability. This skin effect in turn determines the resistance of the wire to the alternating current, and so, finally, measurement of this resistance provides a measure of the magnetic field. Usually two such wires are used together, placed some distance apart; when the magnetic field is uniform, their resistances are equal, but when the pair passes through a region of irregularity, the fields are no longer exactly equal and the balance is disturbed. The method is extremely sensitive, as indeed it must be to be useful,

and differences of field between the pair of wires of as small as a millionth of a gauss can be detected.

3. *The magnetic mine and its antidote*

The magnetic mine, which was such a serious menace to our shipping in the war, is another example of a device working on disturbances of the earth's magnetic field. Basically, the original model consisted of a delicately pivoted dip needle, which, if it turned appreciably from its normal position, closed an electrical contact which detonated the mine. Various complicated automatic devices were incorporated to render the mechanism inactive until it had come into position on the sea bed close to where ships were expected to pass. A ship, since it is mostly made of iron, is magnetized by the earth's field, and if it passed near enough to the mine it sufficiently changed the earth's field direction to turn the dip needle and set off the mine.

To counter this weapon, our scientists worked out two main antidotes. One of them was to destroy the mines as soon as possible after they were laid, and the most effective way of doing this was to fly low over the suspected area in an aeroplane fitted with a huge loop of wire carrying a very large electric current. The magnetic effect of this loop acted in the same way as a ship, and blew up the mine, but as the aeroplane was well above the water and flying fast, it was safe from the explosion. The other antidote has the rather ugly name *degaussing*. It consists in protecting the ship by winding wire cables round the ship. If just the right amount of electric current is passed through each such coil (the currents required run into hundreds of amperes) the magnetic effect of the currents can be made approximately to neutralize the magnetization of the ship due to the earth's field. The ship is then said to be " degaussed " and no longer upsets the

earth's field near it—it can then pass safely over a magnetic mine without exploding it.

4. *The power of a magnet to attract iron*

The attraction of a magnet for pieces of iron is one of the most familar manifestations of magnetism, and has many practical applications. It is instructive to estimate the size of these forces of attraction. Without such an estimate we might be tempted to believe in all sorts of fantastic applications, such as the famous method suggested for catching lions in the desert by feeding them with spinach (which contains iron) and then switching on a powerful magnet.

Any magnet has effectively two poles, and at a distance r, which is fairly large compared to the distance between its poles, the field it exerts is roughly M/r^3, if M is the equivalent dipole strength of the magnet (pole strength $\times$ distance between poles). If a piece of iron is placed in this field it becomes magnetized to an extent depending mainly on its shape (p. 71), and if we suppose it to be a sphere, then its induced magnetic moment is $3/4\pi$ times its volume times the field ; thus

$$\text{Moment of sphere} = \frac{M}{r^3} \times \frac{3}{4\pi} \times V$$

The inhomogeneity of the magnet's field (the rate at which it falls off as r increases) is given by $3M/r^4$, so the force of attraction between sphere and magnet, which is given by inhomogeneity times moment of sphere (see p. 65), is

$$\text{Force} = 9M^2V/4\pi r^7$$

This result (which of course is only true if r is large enough) shows that the force falls off very rapidly with distance, so, returning to our lion-catching problem for a moment, it is unlikely that any lions will be caught unless they come very close to the magnet, and even then they would have to eat a lot more iron than is contained in a reasonable dose of spinach.

In order to put our result into more numerical terms, we now work out how small r has to be before the sphere of our problem is lifted up by the magnet. To do this, the force of the magnet must just overcome the force of gravity, which is $V\rho g$ (where ρ is the density of the sphere, and g the acceleration of gravity). So we have the equation

$$r^7 = 9M^2/4\pi\rho g$$

to determine r. Notice that the size of the sphere does not enter into the answer, though of course the sphere must not be too big, or else our assumptions go wrong. We can make a very rough estimate of M by supposing the gap of the magnet to be a cubical space of side a, then M will be equal to the intensity of magnetization of the magnet times the volume of the gap, which is a^3. If our magnet is a modern permanent magnet, its magnetization will be about 500, and putting $\rho = 8$ gm./cc., $g = 1{,}000$ cm./sec.^{2} (these figures are rough, but good enough for the purpose), we find

$$r^7 = \frac{9 \times (500)^2 \times a^6}{4\pi \times 8 \times 1{,}000}$$

which gives very roughly $r = 1{\cdot}5\ a$.

Quite apart from the approximations in the calculation, the answer can only be very roughly true because it shows that r is only slightly bigger than a, the pole piece gap, while our basic assumptions require that r should be many times a. However, even so, the answer will be accurate enough to give an idea of the size of r, the distance at which a magnet will attract a piece of iron sufficiently to lift it. Once the magnet is brought closer than this, the force gets rapidly bigger and the piece of iron jumps into contact with the magnet, so we can call this critical distance the "jumping distance." The important feature of the result is that this jumping distance is not very much bigger than the size of the magnet gap, so that a piece

of iron (and notice again that the size of the iron does not come into the answer provided the piece of iron is reasonably small) can only be lifted up from very close to.

After making this estimate of the jumping distance, I thought it might be of interest to check it by a simple experiment. Using one of the powerful little horse-shoe magnets given away by magnet manufacturers (see p. 129 and plate VI*b*) I measured the distance at which it would just make its keeper jump from the table. The result of the experiment is shown in fig. 56*a* : the keeper jumps when it is about 2 cm. from the magnet. Now the magnet gap (the " *a* " of the calculation) is about 1·8 cm. (reckoning between the centres of the pole faces),

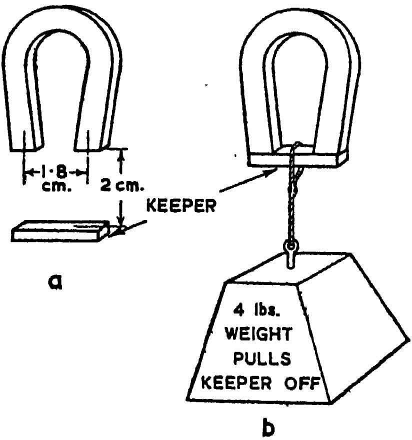

Fig. 56.—Weight-lifting properties of a permanent magnet.

(*a*) At about the position shown, the keeper will jump and stick to the magnet ;

(*b*) Once the keeper has stuck to the magnet, about 4 lb. weight is needed to pull it off again.

so the calculation predicts a jumping distance of 1·5 × 1·8 or 2·7 cm., which, considering all the approximations and the fact that the keeper is not a sphere, is good agreement with the experiment.

The jumping distance is only one feature of the attraction problem ; we want to know also how big the attractive force is once the iron object has jumped and stuck to the magnet poles. If, for instance, the keeper of the horse-shoe magnet is stuck in position (fig. 56*b*) how big a weight can it support? Here again a rough estimate is possible. The force of attraction is now spread evenly over the whole of the pole face area and calculation shows that it is given by

$$\text{Force} = 2\pi I^2 \times \text{area of pole faces}$$

if I is the intensity of magnetization. Putting $I=500$ as before, and 1·8 sq. cm. for the area, this gives a force of 2·7 million dynes, or in more familiar terms about 5 lb. weight. Actually, as illustrated in the diagram, experiment showed that the magnet would hold only about 4 lb. weight : probably 500 is an over-estimate for I, the magnet having become a little weaker since I first had it, because of the frequent slight demagnetizations it has undergone.

The important point of the calculation is that it shows that the weight lifting power of a magnet is determined mostly by the area of its poles, and to lift large weights correspondingly large magnets are required. Some increase can be obtained by using an electromagnet with a soft iron core, for if the current is big enough to saturate the iron core we can get $I=1{,}600$ rather than the 500 of a permanent magnet, and this increases the weight-lifting power about ten times per unit area of the pole faces.

5. *Miscellaneous applications of the attraction of iron to a magnet*

One rather obvious application of these principles

is for sorting out iron from other materials in a scrap heap. The poles of a large electromagnet are pushed into the scrap heap and when the whole magnet is lifted with the current on, it carries with it as much iron as it can lift. To lift a ton at a time, our calculation shows that the magnet must be quite large, with poles about five inches in diameter. Such an electromagnet would weigh something like a hundred pounds itself. A similar method is often used in sorting minerals to separate out the iron-bearing ores from the others. Here the forces may be much smaller than in the case of iron metal, since iron ores are usually much less magnetic, but by suitable design this method of separation can be made to work. A special kind of magnet is sometimes used for removing grit from the eye, since the grit that gets into the eye is often largely iron dust; a magnet designed for this purpose is provided with a pointed pole piece whose very inhomogeneous field produces as large a force as possible.

Another important application is the *magnetic relay* which is at the basis of most automatic and remote control systems. There is a great variety of types of magnetic relay but all depend on the principle that when an electric current is passed through the coil of an electromagnet, a piece of iron is pulled to the pole against the force of a spring which otherwise holds it away. When the iron moves, it closes an electrical contact which switches on current in another circuit. The current used to work the relay is usually much smaller than the current which the relay contact controls, so the relay is useful where heavy currents have to be easily controlled. A typical example is in the running of a lift. When the button is pressed for a particular floor only a small current is started in a particular circuit, but this, by means of the relay, operates a much larger switch which starts the lift motor, and at the same time by way of another relay arranges that

the lift motor will be switched off again when the desired floor is reached. Without the relays, these much larger switches would have to be placed in the lift instead of the much more convenient and safer push buttons.

The automatic telephone system is another example of the use of relays. When you dial a number, a current is interrupted a number of times, and each interruption makes a special kind of relay move from one contact to the next, in a complicated maze of contacts called a selector switch, until finally (if you are lucky) the contacts are arranged so that your line is connected to the telephone line you want. Of course, there is a lot more to it than this, for the system must also arrange to give the various "dialling," "ringing" and "engaged" notes, and it must ensure that different people dialling at the same time do not interfere with each other. To deal with all these points, not only is there an immense number of selector switches, but also many other relays of special types which are "interlocked" in various ingenious ways so that everything goes forward in a definite order. The simplest type of telephone relay is illustrated in plate VIII*d*; when current flows in the coil, the iron plate at the right-hand side is attracted and closes the contacts visible at the top of the relay.

The action of the telephone itself also depends (though in quite a different way) on the attraction of an electromagnet for a piece of iron. Sound consists of rather rapid oscillations of air pressure, the pitch being determined by the frequency of these oscillations (this varies from 10 or 20 cycles per second for very low notes up to several thousands for very high notes). When you speak into the telephone microphone, these pressure oscillations are translated into oscillations of an electric current flowing in the circuit between your microphone and the receiver of the distant telephone.

This alternating current passes through an electromagnet in the receiver to which an iron disc is lightly held. As the current oscillates in a manner controlled by your voice, so the attraction of the disc to the electromagnet also varies, and this makes it vibrate in the same way as the air close to your mouth vibrates. The vibrations of the disc set up pressure oscillations in the air round it, and these are heard as the sound of your voice in the receiver.

The same kind of principle is used in a slightly different way in the moving-coil loudspeaker of modern wireless receivers. Here the alternating currents (again reproducing the oscillations of the original sound which reached the microphone at the transmitter end) pass into a light coil which is attached to a paper or parchment cone. This coil is in the field of a compact permanent magnet and a force acts on it depending on the current in the coil. Thus, as the current oscillates, the paper cone vibrates at the same frequency, and by the pressure variations it creates in the air round it, produces sufficient sound to fill the room.

The last application of the same principle we shall mention is the detection of flaws in iron castings. This is an important problem for steel-makers, since often a small crack or flaw inside the casting (and therefore invisible) may make it useless or unsafe. If the casting is magnetized, the flaw causes an irregularity in the magnetic flux through the casting, and thus can be revealed as a field irregularity at the surface. If the flaw is bad enough, the irregularity of field can be revealed simply by sprinkling iron filings over the surface, and will show up as an irregularity in the otherwise regular arrangement of the filings. We can say, in fact, that the attraction of the magnetized casting for the iron filings on its surface is modified near a bad flaw and the flaw is thus revealed, just as the Bitter patterns revealed the domain structure of a

ferromagnetic (Chapter 5). For less serious defects, more delicate investigation of the surface is necessary and a whole science of "defectology," as it is sometimes called, has grown up in recent years.

6. *Eddy current heating—the modern furnace*

The eddy currents induced in any mass of metal by an alternating field are sometimes a nuisance—as in transformer cores (Chapter 5)—but as is often the case in science, what is a nuisance in one application can be turned to advantage in another. We have already mentioned a metal detector based on eddy currents, and we now come to our last example of the role of magnetism in technology, the use of eddy currents for heating.

Imagine a piece of metal placed in a coil through which alternating current is passing. The changing magnetic field of the current induces electromotive forces round every closed path in the metal (by Faraday's law) and these E.M.F.s drive the so-called eddy currents. Since the metal has electrical resistance, the eddy currents heat it, the power being drawn from the source which provides the alternating current in the coil. A calculation based on Maxwell's electromagnetic equations (Chapter 2) shows that the heating effect per unit volume increases as the square of the strength of the alternating field, as the square of the frequency and the square of the size of the metal. Thus, in order to make the heating effect as large as possible, powerful sources of high frequency currents are required and the metal must be large (but not too large or else the theory is modified, and the heating no longer increases with size). In this way the temperature can be raised very high and an interesting feature is that as the temperature rises, the heating effect increases still further owing to the fact that the electrical resistance rises with temperature.

This principle finds many applications in modern technology. It provides a very convenient way of melting metals and has the advantage that since the heat is developed only in the metal itself, the surrounding vessel remains fairly cool, if it is made of an electrical insulator. In the preparation of alloys of two or more different metals, it has a further advantage, since when the metals melt the mechanical force of the alternating magnetic field acting on the eddy currents it produces, is able to stir up the liquid metal and mix up the alloy much more thoroughly than any other method.

Eddy current heating is used also in the manufacture of valves. It is essential to leave a very high vacuum in a radio valve, and, unless the various metal parts within the glass envelope are very thoroughly heated before the glass is "sealed off," traces of occluded gas will slowly come out of the metal in the course of time, and thus ruin the vacuum and make the valve useless. This heating is very conveniently done by the eddy current method, and indeed it could hardly be done without it. Just before the valve is sealed off from the vacuum pumps, it is surrounded by a small coil through which a large high frequency current is passed. The eddy currents induced in the metal parts flash them up to white heat and all traces of gas are rapidly driven off, without the glass envelope becoming appreciably hot.

BIBLIOGRAPHY

The following list is designed to help those who would like to learn more about some of the topics in this book. Not every topic is covered in this list, because some are dealt with only in very advanced texts or original scientific papers ; references to such sources will be found in the books listed below as " for more detailed study."

E. C. Stoner " Magnetism and Matter " (Methuen)
L. F. Bates " Modern Magnetism " (C. U. Press)
F. Brailsford " Magnetic Materials " (Methuen)

For more detailed study of the whole subject, and particularly of Chapters 3, 4 and 5: Stoner's book contains, too, an interesting historical introduction.

W. L. Bragg " Electricity " (Bell)
J. G. Daunt " Electrons in Action " (Sigma Books)

Popular accounts of electricity and its relation to magnetism, which cover much of Chapter 2 in greater detail, and also some of the practical applications touched on in Chapter 8.

S. G. Starling " Electricity and Magnetism " (Longmans)
F. B. Pidduck " A Treatise on Electricity " (O. U. Press)
R. Becker " The classical theory of electricity and magnetism " (Blackie)

These are three books for more detailed study of the topics in Chapters 2 and 3 ; they are roughly in order of difficulty, Starling being the most elementary and

Becker the most advanced. Many of the formulae quoted without proof in Chapters 2 and 3 are worked out fully in these books.

J. A. Ratcliffe " Physical Principles of Wireless " (Methuen)

For more detailed study of wireless (Chapter 2).

O. R. Frisch " Meet the Atoms " (Sigma Books)
K. Mendelssohn " What is atomic energy?" (Sigma Books)
M. Born " Atomic Physics " (Blackie)

Fairly popular accounts of atomic theory (Born's book is more advanced) which will help in understanding the beginning of Chapter 4 and parts of Chapter 7.

S. Chapman " The Earth's Magnetism " (Methuen)

For more detailed study of Chapter 6.

D. S. Evans " Frontiers of Astronomy " (Sigma Books)

His chapter 6 has a good account of sun-spots (mentioned in our Chapter 6).

J. G. Wilson " About Cosmic Rays " (Sigma Books)
W. B. Mann " The Cyclotron " (Methuen)
S. Ellwood " Magnetochemistry " (Interscience Publishers, N.Y.)

For more detailed study of the topics indicated.

GLOSSARY—INDEX

Absolute temperature	59	Is obtained by adding 273 to ordinary Centigrade temperature.
Adiabatic demagnetization	177, 180	A process in which a salt is thermally isolated and removed from a magnetic field, thus cooling the salt to super-low temperatures.
Alpha (α) particles	157	Emitted by certain radio-active substances; they are the nuclei of helium atoms, and four times as heavy as protons.
Alternating current (A.C.)	40	Electric current which changes its direction of flow periodically, many times a second.
Ammeter ..	35	An instrument for measuring electric currents.
Ampere ..	14, 44	The practical unit of electric current.
Ampère's law ..	28	States that the magnetic effect of an electric current is the same as that of an equivalent magnetic shell.
Amplitude ..	46	The maximum size of a quantity which is varying harmonically; for instance, the peak value of an alternating current.
Angular momentum	85, 90	Is obtained by multiplying the mass of a rotating particle by its velocity and the radius of the circle in which it rotates. For a solid body, rotating about

		a fixed axis, the angular momentum is the sum of the angular momenta of the particles of which the body is made. For a sphere, for instance, this works out as $\frac{2}{5}$ its mass times the square of its radius times its *angular velocity*.
Angular velocity ..	202	Rate of change of angle.
Atomic number ..	77	The number of an element if all the elements are arranged in order of their atomic weights. It is also the number of electrons in the atom.
Atomic weight ..	75	The ratio of the weight of an atom to that of a hydrogen atom.
Beta (β) rays ..	167	Very fast moving electrons emitted by certain radio-active substances.
Betatron ..	42, 175	A machine for accelerating electrons to very high speeds.
Bitter patterns ..	109	Patterns obtained by sprinkling fine ferromagnetic powder on the surface of a ferromagnetic, thus revealing the domain structure.
Bohr magneton ..	85	The fundamental unit of magnetic moment. It is the magnetic moment of an electron rotating in the simplest quantum orbit of an atom and has a value $e\hbar/2m = 9 \times 10^{-21}$.
Boltzmann's constant	81	Is fundamental in statistical mechanics; it measures the violence of thermal agitation. Its value is $k=1{\cdot}38\times10^{-16}$ ergs/degree, and $k \times$ Absolute temperature measures the energy of thermal agitation.

Cathode rays ..	166	A stream of electrons produced in an evacuated tube subjected to high potential.
Coercive force ..	57	The reverse magnetic field required to demagnetize a permanent magnet which has previously been magnetized to saturation.
Corkscrew rule ..	28	States that the direction of a magnetic field is related to the sense of the current producing it in the same way as the direction of progression of a corkscrew is related to the sense of turning it.
Cosmic rays ..	169	Very high energy radiation reaching the earth from outer space.
Coulomb's law ..	13	States that the force between two poles is inversely proportional to the square of the distance between them.
Couple	15	A pair of equal and opposite forces acting along parallel lines. A couple has a twisting action measured by one of the forces times the distance between the two.
Critical field of a superconductor	105	The maximum magnetic field in which superconductivity can exist. For higher fields normal conductivity is restored.
Crystal ..	76, 111	A piece of solid matter in which the atoms or molecules are arranged in a regular lattice framework. The directions of the axes of the lattice framework stay the same all through a *single crystal* or *crystal grain*.
Curie's law ..	59	States that the susceptibility of an ideal paramagnetic substance

		varies inversely as the absolute temperature.
Curie point ..	60	The temperature above which ferromagnetism disappears.
Curie-Weiss law ..	60	States that the susceptibility of a ferromagnetic substance *above* its Curie point is inversely proportional to the amount its temperature is above the Curie point.
Current element ..	31	A very small piece of a circuit in which an electric current flows.
Cycle	40	The variation from one peak to the next in A.C.
Cyclotron.. ..	172	A machine for accelerating atomic particles to very high energies, for the purpose of smashing other atomic nuclei.
Declination ..	140	The angle between the direction in which a compass sets and the true north. Sometimes called *variation*.
Degaussing ..	189	Making a ship safe against magnetic mines by winding coils round the ship and passing enough current through the coils to neutralize the ship's magnetism.
Demagnetizing field	69, 70	The field produced within a body by its own magnetization. This field opposes the field producing the magnetization.
Deuteron	174	The nucleus of a heavy hydrogen atom (heavy hydrogen is the isotope of hydrogen with atomic weight 2).
Diamagnetic ..	54	A substance which becomes magnetized in a direction opposite

		to the magnetizing field. It tries to move into the weakest part of a magnetic field.
Dip angle..	.. 139	The angle between the direction of the earth's magnetic field and the horizontal.
Dip circle..	.. 139	A magnetized needle pivoted on a horizontal axis. If set with its plane of rotation in the magnetic meridian it sets along the earth's magnetic field and so measures the dip angle.
Dipole ..	.. 22	The limiting case of a short magnet, when the magnet is made shorter and shorter, and the poles stronger and stronger so that the magnetic moment does not get smaller.
Direct current (D.C.)	40	Current which flows continuously in the same direction.
Displacement current	.. 41	A special kind of current associated with changing electric fields.
Domain ..	.. 99	A region of a ferromagnetic in which the spontaneous magnetization has a constant direction.
Dynamo ..	.. 39	A machine which generates electricity by the motion of wire circuits in magnetic fields.
Dyne ..	.. 13	The unit of force in the metric system. It is the force which would accelerate 1 gram with an acceleration of 1 cm. per sec per sec, and is approximately equal to the weight of 1 milligram (0·001 gm.).
Easy directions of magnetization	113	Particular directions in a ferromagnetic material along which

		the magnetization can occur naturally. These directions are either particular axes in a single crystal or are determined by the mechanical stresses.
Eddy currents	105, 124, 197	The currents induced in a mass of metal by a changing magnetic field. They are sometimes used for heating purposes.
Electromagnet ..	157	A device for producing a magnetic field by means of an electric current.
Electromagnetic induction	38	The production of an electromotive force by a changing magnetic field. This electromotive force can drive a current in a closed circuit.
Electromagnetic units	43	The system of units based on measuring electric currents by their magnetic effects.
Electromotive force (E.M.F.)	38	Measures electric pressure, or the tendency to produce electric current. Sometimes called potential difference.
Electron	77, 167	A minute particle which carries a negative electric charge. This charge is believed to be the smallest quantity of electricity which can exist. Electrons are an important constituent of atoms.
Electron spin ..	87	An electron is believed to behave like a spinning top. With this spinning motion both angular momentum and a magnetic moment are associated.
Electrostatic units	43	The system of units based on the electrostatic measurement of electric charge (by the force between charges).

Element	74	One of the 94 chemical species of which all matter is made.
Erg	81	The unit of energy in the C.G.S. system. It is the work done when a force of 1 dyne causes a displacement of 1 cm.
Faraday's law of induction	38	States that the E.M.F. induced in a circuit is equal to the rate of decrease of the magnetic flux through the circuit. (See Electromagnetic induction.)
Ferromagnetic	8, 54	A substance which is very strongly magnetizable and becomes saturated in comparatively low magnetic fields.
Field, magnetic ..	14	Is measured by the force acting on a unit magnetic pole.
Flux, magnetic ..	38	The flux through a circuit is the strength of the field (perpendicular to the circuit) multiplied by the area of the circuit.
Frequency ..	40	The frequency of an alternating current is the number of complete cycles of change it performs per second.
Frequency modulated cyclotron	163, 175	Another name for a synchrocyclotron (q.v.).
Galvanometer ..	35	A sensitive form of ammeter.
Gauss	15	The unit of magnetic field; it is a field that acts with unit force (1 dyne) on a unit pole.
Grain, crystal ..	111	See crystal.
Gyromagnetic effect	91	The slight tendency of a body to twist when it is magnetized; first discovered by Einstein and de Haas.
Hard material ..	57	A ferromagnetic which requires a large field to saturate it and

		which has a broad hysteresis loop and high coercive force. Suitable for permanent magnets.
Hysteresis ..	57	The tendency of the magnetization curve to follow a different path when the field is reduced, from that which it followed when the field was first increased. If the field is varied through a complete cycle of change, the magnetization traces out a closed curve called a *hysteresis cycle*.
Ideal paramagnetic	100	A paramagnetic which obeys Curie's law to very low temperatures.
Induced magnetism	7	The magnetism produced in a substance by an applied magnetic field, in contrast to *permanent magnetism* which is retained even without any applied field.
Induction, magnetic	52	The magnetic field within a magnetic material measured in a thin disc-shaped cavity which has its plane perpendicular to the field direction.
Inhomogeneity of field	65	The rate of change of field with position.
Intensity of magnetization	24	See magnetization.
Inverse square law	13	Another name for Coulomb's law (q.v.).
Ion ..	93, 168	An atom which has lost or gained one or more electrons and thus acquired positive or negative charge. This process is called

		ionization and takes place for instance under the influence of ultra violet light.
Ionization ..	147	See Ion.
Isogonic lines ..	140	Lines joining points on the earth which have equal declination.
Isotopes	167	Variants of the same kind of chemical species, which differ only in their atomic weight, but have the same atomic number.
Keeper	129	A soft iron bar used to close the gap of a permanent magnet.
Langevin's theory	78	The first theory of para- and diamagnetism in terms of the properties of single atoms.
Lines of force ..	16	Lines which everywhere show the direction of magnetic field. They provide a kind of map of the field.
Lodestone ..	5	The first permanent magnet material to be discovered ; it is a naturally occurring form of magnetite.
Magnetic equator	137	The great circle of the earth equidistant from the magnetic poles.
Magnetic field ..	14	See field, magnetic.
Magnetic flux ..	38	See flux, magnetic.
Magnetic induction	52	See induction, magnetic.
Magnetic latitude	136	Latitude measured from the magnetic equator.
Magnetic longitude	139	See Magnetic meridian.
Magnetic meridian	139	The vertical plane pointing towards the magnetic north pole ; it contains a line of *magnetic longitude*.
Magnetic moment	22	The pole strength of a magnetized body multiplied by the distance between the poles.

Magnetic (or β-ray) spectrograph	169	An instrument for analysing the distribution of velocities of β-rays.
Magnetic pole ..	12	See pole, magnetic.
Magnetic shell ..	25	A sheet which is magnetized in a direction perpendicular to its surface. The magnetic moment per unit area of the shell is called the *strength* of the shell.
Magnetic storm ..	148	A relatively large irregular disturbance of the earth's magnetic field.
Magnetic susceptibility	53	See susceptibility, magnetic.
Magnetization	24, 55	The magnetic moment per unit volume of the substance. If the magnetization is plotted against the field producing it, we get a *magnetization curve*.
Magnetostatics ..	7	The study of the fields due to permanent magnets.
Magnetostriction	117	The small change of length of a body when it is magnetized.
Magnetron ..	176	A device for producing very short wireless waves.
Mass spectrograph	167	An instrument for measuring the atomic masses of isotopes.
Meson	171	A particle about 200 times heavier than the electron; found in cosmic rays.
Molecule	75	A combination of two or more atoms.
Molecular field ..	96	A field proportional to the magnetization, introduced in Weiss' theory of ferromagnetism.
Molecular weight	75	The ratio of the weight of a molecule to that of a hydrogen atom.

Monatomic gas ..	92	A gas whose particles are single atoms, not combined to form molecules.
Mu-metal ..	188	An alloy whose high permeability is sensitive to the value of the magnetic field.
Nucleus	77	The positively charged core of an atom. It carries nearly all the weight of the atom but is much smaller in size than the atom (about 10^{-13} cm. compared with about 10^{-8} cm.).
Parallelogram of forces	19	A geometrical construction for calculating the resultant of two forces (or any two vectors) which act in different directions (see also vectorial addition).
Paramagnetic ..	53	A substance which is magnetized in the same direction as the magnetizing field. It tries to move into the strongest part of a magnetic field. Although these remarks apply also to ferromagnetics, the term paramagnetic is usually reserved for fairly weakly magnetic paramagnetics.
Paramagnetic, ideal	100	See ideal paramagnetic.
Permalloy ..	126	A high permeability alloy of nickel and iron suitable for use in small transformers.
Permeability ..	53	The ratio of magnetic induction to magnetic field.
Photoelectric effect	166	The emission of electrons under the influence of light.
Pole, magnetic ..	12	The magnetic poles of a long thin magnet are the two end points from which the magnetic action

		of the magnet seems to come. For any other shape of body the poles are smeared over the whole surface.
Pole piece . .	157, 162	The termination of the core of an electromagnet or permanent magnet.
Polycrystalline material	112	Material which is made up of many single crystal grains oriented at random.
Positron . .	. . 171	A particle of mass equal to that of the electron, but positively instead of negatively charged.
Proton . .	. . 164	The nucleus of a hydrogen atom.
Quantum . .	. . 85	The basic unit of angular momentum ; it is denoted by $\hbar$.
Radio fade-out	. . 152	A disturbance of radio transmission caused by changes in the ionized layers of the upper atmosphere. Such changes are associated also with disturbances of the earth's magnetic field.
Relay, magnetic	. . 194	A device by which a small current is able to control a remote switch which makes and breaks a larger current. Much used in the telephone service.
Remanence	. . 57	The magnetization retained by a ferromagnetic when a field sufficient to saturate it has been applied and removed. The ferromagnetic should be in a form which eliminates demagnetizing effects (e.g. a long thin rod) or the retained magnetization will be less than the true remanence.

Resultant	19	The single force which represents the combined effect of two forces acting in different directions. This resultant force can be calculated by means of the parallelogram of forces (q.v.).
Saturation	55, 97, 102	The state in which further increase of magnetizing field causes no increase of magnetization. The term saturation is often used as an abbreviation for the magnetization at saturation.
Secular variations	146	Changes in the characteristics of the earth's magnetic field which take place gradually (over many years), in contrast to more rapid changes which either have a regular periodicity or are completely irregular.
Self-inductance ..	38	A property of a coil which has the effect of increasing its resistance to alternating current.
Shell, magnetic ..	25	See magnetic shell.
Skin effect ..	188	The tendency of a high frequency electric current to be concentrated on the outer surface of the wire in which it flows.
Soft material ..	57	A ferromagnetic which requires a small field to saturate it and which has a narrow hysteresis loop and low coercive force. Suitable for transformer laminations.
Solenoid	30	A long coil of wire, which produces a uniform magnetic field inside its central portion, when current flows in the coil.

Spectroscope ..	153	A device for producing a spectrum.
Spectrum ..	87, 153	A distribution of light in which the various wavelengths (i.e. colours) present are spread out and appear separated from each other.
Spin, electron ..	87	See Electron spin.
Statistical mechanics	80	The study of the behaviour of large assemblies of particles in thermal equilibrium.
Sun-spot activity ..	149	The extent to which the surface of the sun is covered by sun-spots. Quantitatively it is measured by assigning a *sun-spot number*.
Superconductivity	105	The property of some metals to lose all their electrical resistance at very low temperatures. In the superconducting state such metals do not allow a magnetic field to enter and so are strongly diamagnetic.
Susceptibility, magnetic	53	The ratio of magnetization to magnetizing field is called the *volume* magnetic susceptibility. Divided by the density it becomes the *mass* susceptibility, and divided by the number of atoms or molecules in unit volume, it becomes the *atomic* or *molecular* susceptibility.
Synchro-cyclotron	163, 175	A cyclotron in which particularly high energies are achieved by synchronously modulating the frequency of the alternating field.
Thermionic effect	166	The emission of electrons from hot metals.

Transformer ..	123	A device consisting of a *primary* and a *secondary* coil, such that a low alternating voltage across the primary coil becomes transformed into a high alternating voltage across the secondary coil.
True north ..	140	The geographical north direction, pointing towards the geographical north pole of the earth, where the axis of the earth's rotation meets the earth's surface.
Uniform field ..	20	A field which does not vary in magnitude or direction. Any field can be considered as uniform over a sufficiently limited region.
Variation	140	See Declination.
Vectorial addition	19	The method of adding two forces or other *vectors* (quantities which have direction as well as magnitude) not in the same direction, by means of the parallelogram of forces (q.v.).
Velocity spectrum	169	A spectrum in which a mixture of particles of various velocities is spread out according to velocity. For instance a β-ray spectrograph produces a velocity spectrum of β-rays.
Volt ..	14, 44	The practical unit of electric potential or E.M.F.
Wavelength ..	45	The distance between neighbouring crests of a wave. Yellow light has a wavelength 6×10^{-5} cm., but wireless waves are hundreds of metres long.

Weiss' theory of ferromagnetism	96	The theory that ferromagnetism is due to the existence of spontaneously magnetized domains. These domains are believed to be magnetized by the strong interaction forces between the elementary magnets of the material. In Weiss' theory this interaction is represented by a molecular field (q.v.) proportional to the magnetization.
Wilson cloud chamber	169	A device by which the tracks of fast-moving charged particles (such as ions and electrons) are made visible.
Zeeman effect ..	153	The effect of a magnetic field in changing the wavelength of light. A spectral line originally of a single wavelength splits into several lines of slightly different wavelengths when the source of light is in a magnetic field.